NASA Contractor Report 3345

Electrostatic Protection of the Solar Power Satellite and Rectenna

Part II - Lightning Protection of the Rectenna

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Electrostatic Protection of the Solar Power Satellite and Rectenna

Part II - Lightning Protection of the Rectenna

Rice University
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National Aeronautics
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SUMMARY AND CONCLUSIONS

1. The very high lightning flash density in many parts of the United States and the large size of the SPS rectenna require us to incorporate lightning protection systems in the rectenna design.

2. A distributed lightning protection system is described in this report that will protect the rectenna components from direct lightning strike damage and will, in addition, provide reduced induced lightning effects in the power and control circuits.

3. The proposed lightning protection system should be incorporated as a structural member of the rectenna support system; viewed as such, the lightning protection system will not appreciably increase the total material requirements for the rectenna unless materials are used that are incapable of safely conducting lightning currents.

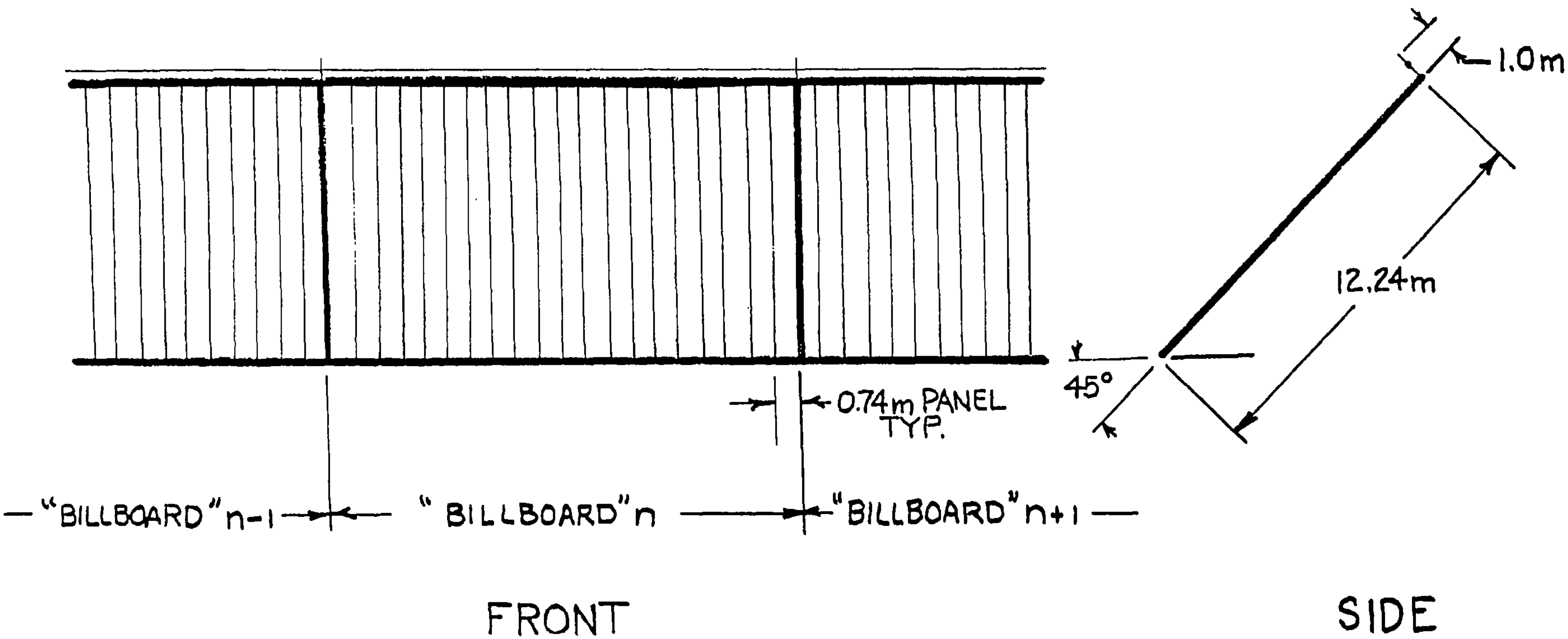
4. The lightning protection design places the conducting elements so that the microwave shadow cast by protection systems falls along the upper edge of the billboard on which it is mounted (and the lower edge of the next billboard to the north); these shadow areas are only a slight fraction of the collecting area, so the protection elements produce very little, if any, additional power loss to the rectenna as a whole.

5. Individually the microwave diodes are self-protecting with respect to "average" lightning and those near the center of the rectenna are safe from extreme lightning. However, the series connection of the diodes to form 40,000 V strings creates a protection requirement for the string. Standard surge protection practices are necessary for the string.

6. Electric power industries usually attribute 10% of the cost of power transmission equipment to lightning protection requirements. If this factor is not already included in cost estimates, it should be added.

SUMMARY OF THE RECOMMENDED LIGHTNING PROTECTION DESIGN

Based upon our research, computer simulations, and laboratory tests with a scale model, we recommend a distributed lightning protection system that employs a horizontal conducting member with points and grounds placed at every bay or billboard (14.69 meters apart). This configuration not only provides greater protection than other configurations that were evaluated, it is more easily integrated into the structural design of the rectenna. The recommended system is shown in Figure 1.



DISTRIBUTED LIGHTNING PROTECTION SYSTEM

FIGURE 1

PREFACE

The objectives of this study are to evaluate the hazard posed by lightning flashes to ground on the SPS rectenna and to make recommendations for a lightning protection system that will provide sufficient protection to the rectenna. For purposes of this study, the SPS rectenna design is based upon the data supplied to us by Rockwell International in July, 1978.

This study has four major components, each with several elements of investigation. The components were: lightning distribution; lightning interactions; rectenna damage estimates; rectenna protection. The elements of each component are listed in Table A. The study plan was to proceed from top to bottom evaluating the elements listed in each component; work proceeded in a parallel manner for the four components. The organization of this final report reverses this order by presenting the more important results of the study first, then following this with the material and considerations leading to the conclusions.

TABLE A

Rectenna Electrostatic Protection

Lightning Distribution	Lightning Interactions	Rectenna Damage Estimates	Rectenna Protection
1. Obtain climatological data.	1. Review/compile data on lightning parameters.	1. Diode failure modes (scaled from available diodes.)	1. Panel transient protectors.
2. Format data for computer use.	2. Construct program for computation of fields and currents in the rectenna plane from parameterized lightning	2. Insulation breakdown.	2. Billboard surge protectors.
3. Construct program for computation of lightning density.	3. Evaluate enhancement factors.	3. Direct strike damage estimates.	3. Lightning Inverter protectors
4. Produce contour map of lightning density.	4. Conduct laboratory simulations.	4. Direct strike damage estimates.	4. Lightning rod systems.

Hazard Evaluation
Statistical Evaluation
of Lightning Effects

Rectenna Design
Recommendations for
Electrostatic Protection

Final Report

The Principal Investigator was J.W. Freeman, Jr., and the principal author of this section of the final report was A.A. Few, Jr. They wish to express their thanks and appreciation to the following co-authors, all of whom were or are associated with Rice University.

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I. ANALYSIS OF LIGHTNING ROD PROTECTION CAPABILITIES FOR A CONFIGURATION SUITABLE TO THE RECTENNA

1. Cone of Protection Considerations:

I. 1.1 Definition and Considerations

The capability of a vertical conductor to attract a lightning flash is described by the cone-of-protection, or perhaps more accurately the cone-of-attraction. In theory, any lightning flash that would have entered this cone had the vertical conductor not been in place, will strike instead the conductor and be shunted to the ground. The method by which this process takes place is as follows:

> The lightning stepped leader creates high voltages over a wide area on the rectenna because of the large charge on the leader tip. At points on the rectenna where the electric field reaches breakdown values due to local enhancement factors, upward propagating sparks are initiated which move to meet the downward propagating stepped leader. The upward propagating spark which first makes contact with the leader completes the electrical circuit and the lightning flash current will pass through the structure that initiated the successful upward going spark.

The cone of protection is primarily a function of the height of the vertical conductor because of the field-enhancement factor which enables the taller object to initiate the upward spark before lower objects. Other factors enter into the consideration of the cone of protection, such as the charge on the leader tip and the velocity of the leader, because these factors strongly influence the timing of the production of upward sparks and the height at which the spark and leader meet. In general, the results of research into this subject have shown that the larger the leader charge, then the larger the angle β of the associated cone of protection. Since larger leader charges are usually associated with the larger lightning currents, we find a fortunate result that the cone of protection increases with the potential hazard of the lightning flash.

It follows then that the angle β of the cone of protection (See Figure 2) varies with the particular lightning flash. $\beta = 45^0$ is a very commonly used design angle in the United States and many of the examples in this report employ $\beta = 45^0$.

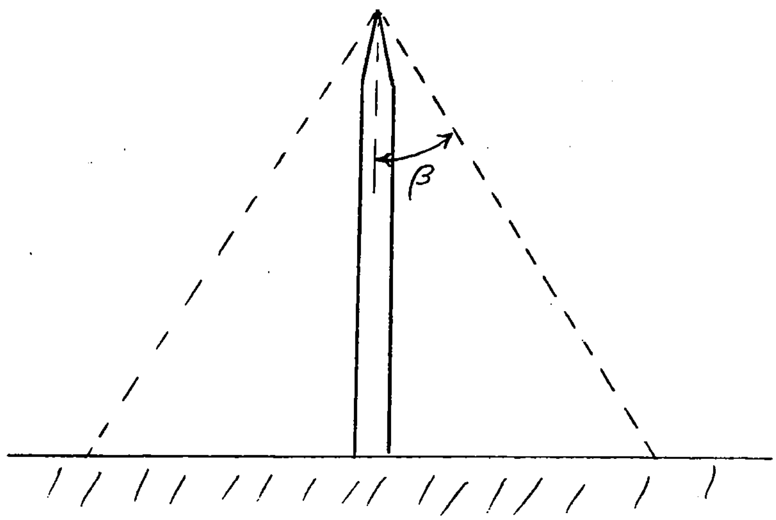


Figure 2

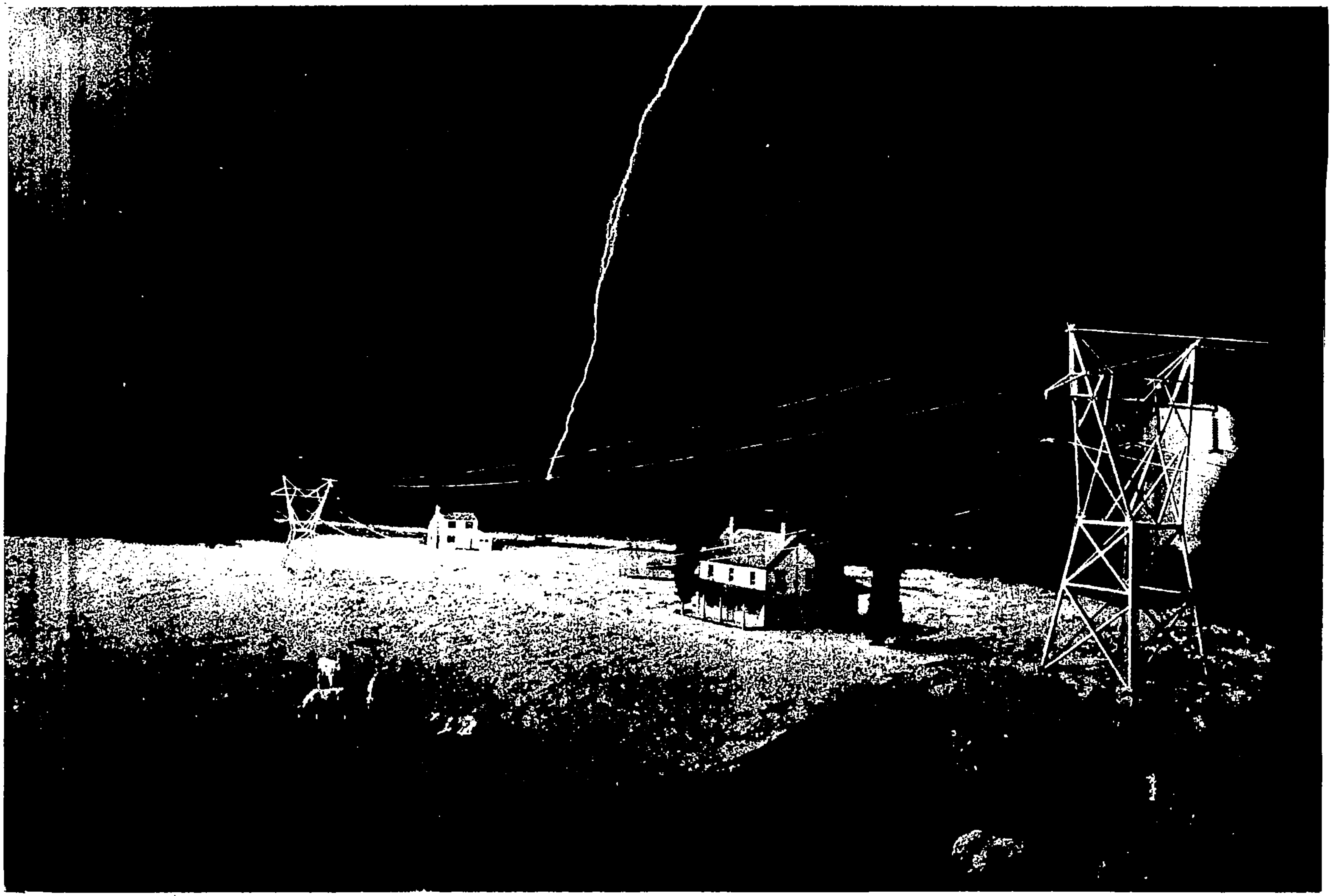
1.2 Distributed Lightning Protection Systems

The cone of protection and the experimental data used to evaluate are specifically related to the single elevated point, and in most cases the system under consideration is 10 to 100 meters in height. As will be seen later, lightning protection of the rectenna falls into a class of structures that requires distributed lightning protection tactics. Figure 3 illustrates a distributed system used by power transmission companies. The main point is that the cone of protection concept is of limited usefulness in the total protection problem. We will use it on the panel and billboard scale as a technique to make a comparative assessment of capabilities of various configurations.

2. Lightning Rod Protection Configurations Compatible with the SPS Rectenna

We have considered three different configurations of lightning rod systems in this effort. In the smallest scale system considered each rectenna panel (0.74m in width) had a short lightning rod attached; see upper example in Figure 4. In the medium scale system each rectenna support structure (14.69m apart) or billboard will have an attached lightning rod; see middle example in Figure 4. And, in the distributed protection system, short terminals located on each rectenna support structure (14.69m apart) were connected by horizontal conducting structures; see lower example in Figure 4.

As seen in the analysis of the billboard scale system, it is impractical to seriously consider larger scale systems.



POWER LINES EMPLOY DISTRIBUTED LIGHTNING PROTECTION SYSTEMS. THIS ILLUSTRATION SHOWS A "STATIC" OR GROUNDED PROTECTION WIRE TAKING A STRIKE AND PROTECTING THE POWER LINES BELOW.

FIGURE 3

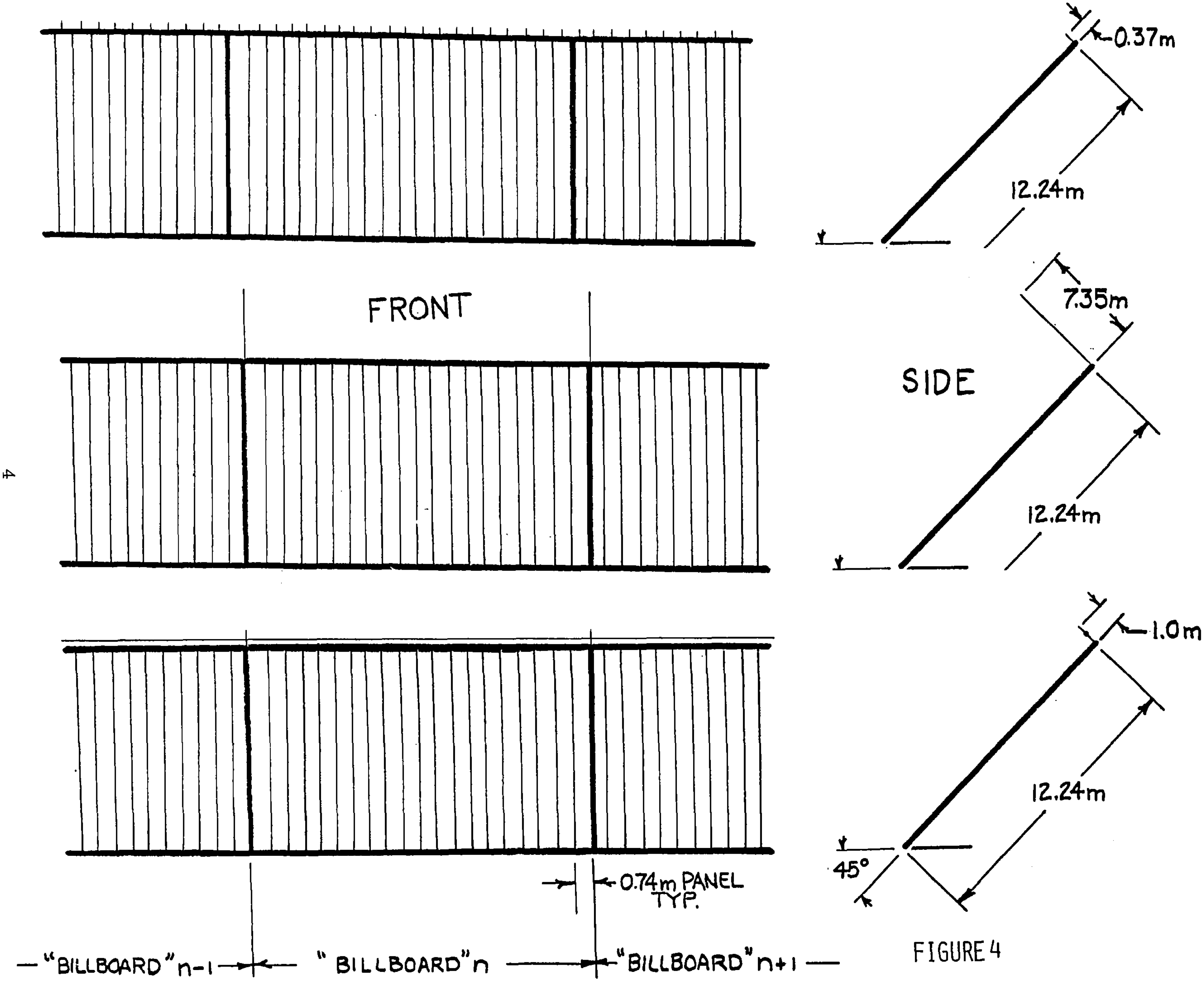
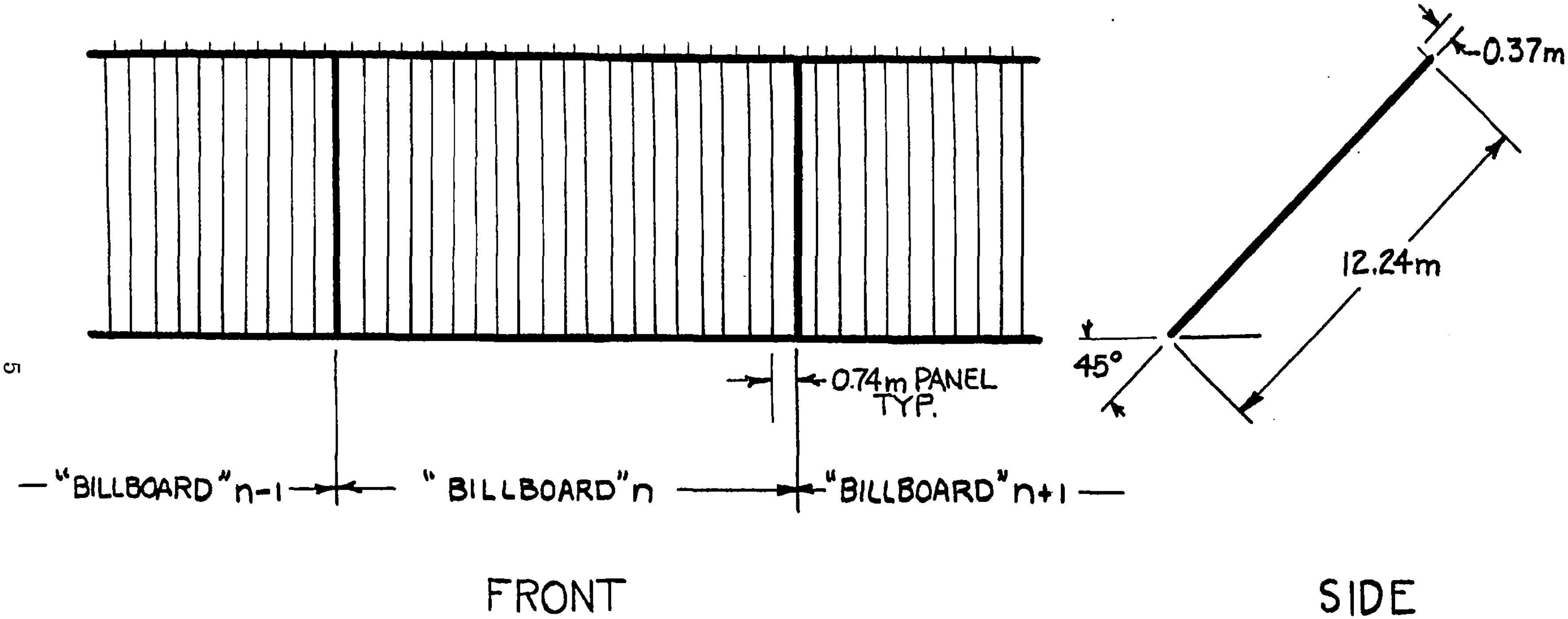

0.37m
12.24m
FRONT
7.35m
SIDE
12.24m
1.0m
12.24m
45°
0.74m PANEL TYP.
"BILLBOARD" n-1
"BILLBOARD" n
"BILLBOARD" n+1

FIGURE 4



PANEL SCALE LIGHTNING PROTECTION SYSTEM

FIGURE 5

2.1 Lightning Rod Protection at the Panel Scale

In this system configuration a relatively short lightning rod is positioned at the top of each panel and oriented perpendicular to the panel face (see Figure 5). Conceptually the rod is centered on the top of the panel, but in practice it could be on the panel edge without altering the results of this analysis.

Let α be the inclination of the rectenna. Figure 6 illustrates the case where β, the angle of the cone of protection, is greater than α. This figure applies only to the conditions in the vertical plane that passes through the lightning rod and is perpendicular to the rectenna face. In this particular projection it appears that the short (example 0.74m) lightning rod on the panel provides adequate protection to the rectenna. In other projections we see that there are, however, "holes in the armor."-

Figure 7 is an enlargement (x10) of the lightning rod portion of Figure 6, and defines the parameters to be used in the following discussions. The cone of protection intersects the plane of the rectenna to form conic sections:

(1) If $\alpha + \beta = 90^0$ the intersection is a parabola.
(2) If $\alpha + \beta < 90^0$ the intersection is an ellipse. (this is the case illustrated in Figures 6 & 7)
(3) If $\alpha + \beta > 90^0$ the intersection is a hyperbola.

If we now look at the intersection of the cone of protection with the panel for the specific cases above, we see the emergence of the protection problem with this type of lightning rod protection configuration. From the geometry of Figure 7 we see that the axis of the cone is at $\ell = L \tan \alpha$ and that the vertex of the conic is at $d = L \tan(\beta - \alpha)$ relative to the top of the panel.

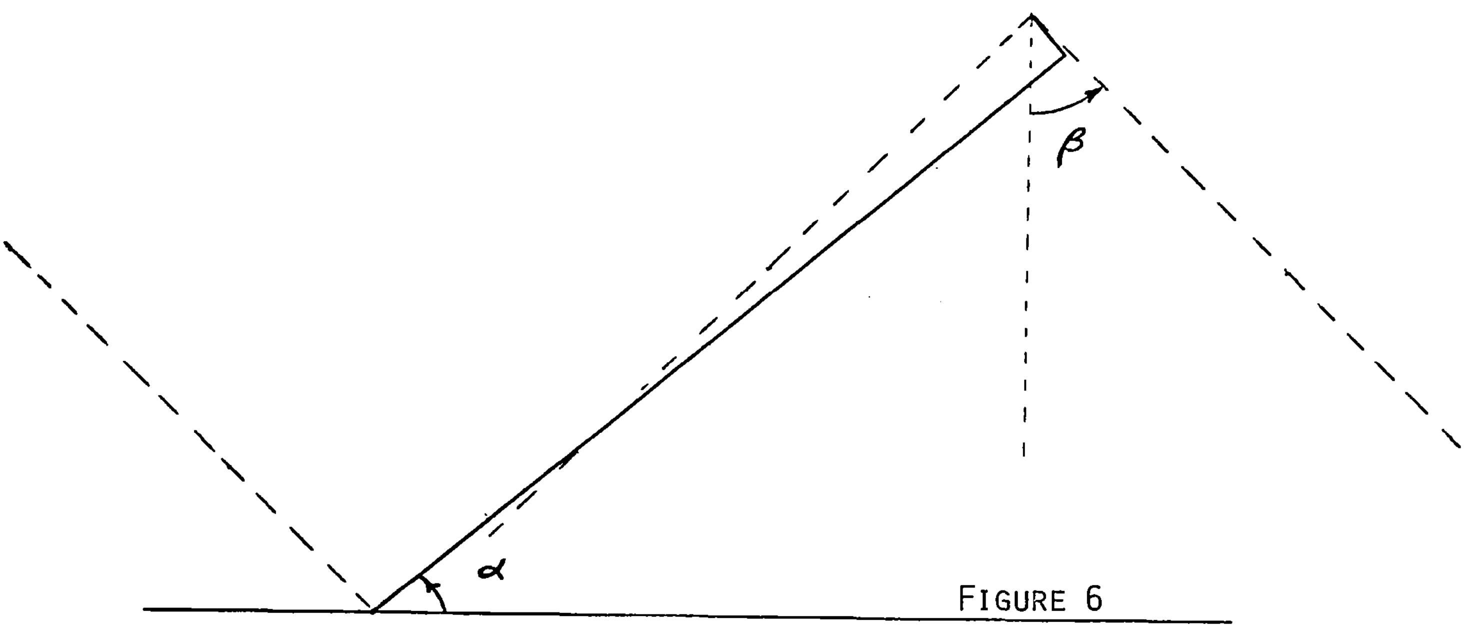


FIGURE 6

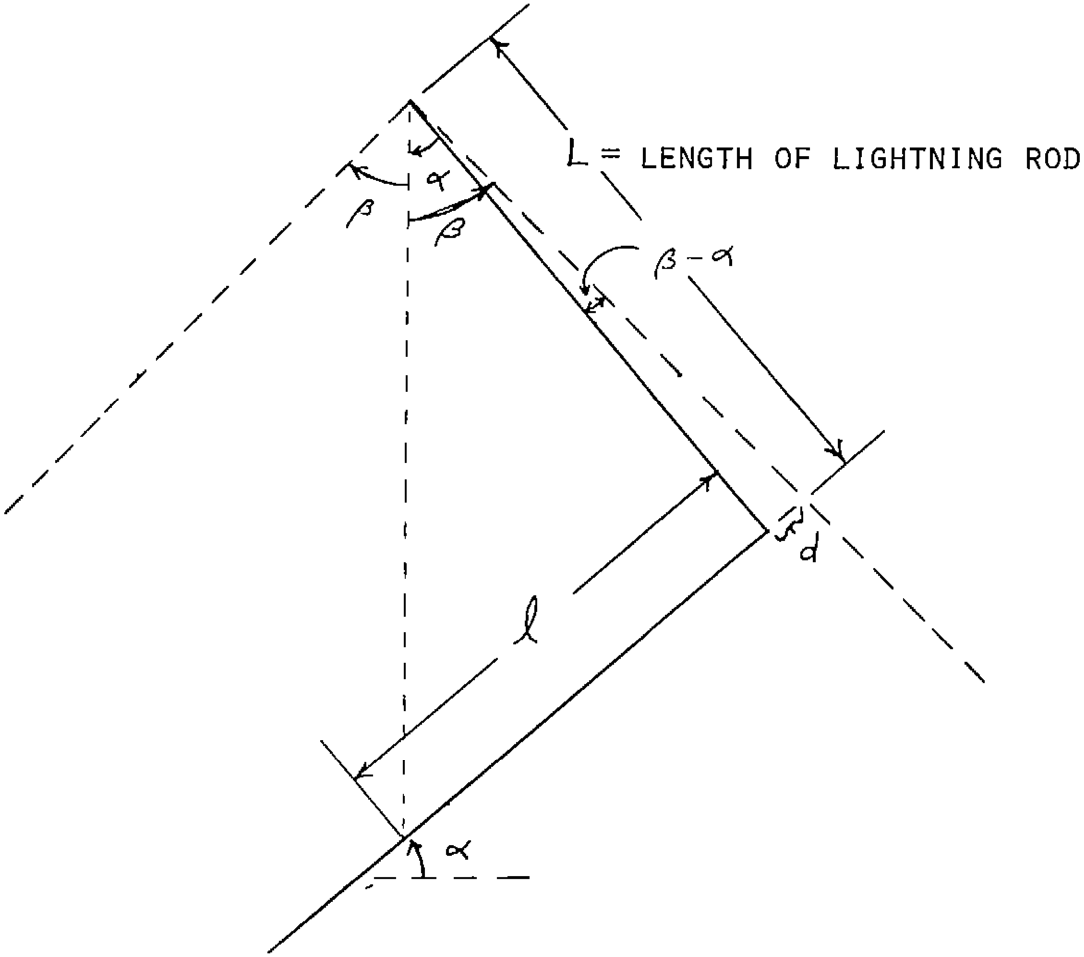


FIGURE 7

ENLARGED VIEW OF THE UPPER END OF THE RECTENNA IN FIGURE 7.

In a coordinate system defined in the rectenna plane with the origin at the axis of the cone and the y axis directed north (toward top of rectenna) and the x axis directed east, the equation for conic is:

$$\frac{x^2\cos^2\alpha}{L^2\tan^2\beta} + \frac{y^2(\cos^2\alpha - \sin^2\alpha\tan^2\beta)\cos^2\alpha}{L^2\tan^2\beta} + \frac{2y\sin\alpha\cos\alpha}{L} = 1$$

For the parabolic solution this equation reduces to:

$$x^2 = -\frac{2L\sin^2\beta}{\cos\beta\cos\alpha}\left(y - \frac{L}{2\cos\beta\cos\alpha}\right)$$

In figure 8 we have plotted the intersection of cones of protection for three lightning rods of lengths 0.185m (= 1/4 panel width), 0.37m (= 1/2 panel width), and 0.74m (= panel width.)

In these examples the rectenna inclination angle α is taken to be 45° and the cone of protection β is equal to 45°. The resulting intersections are parabolas for the cases depicted in Figure 8. For the parabolic solution the cone of protection is parallel to the face of the rectenna in the vertical plane bisecting the panel (The view of Figure 6 and 7 except that here $\alpha = \beta = 45^0$).

At lower latitude sites (below 40°) the rectenna inclination angle α is less than 45° and the 45° cone of protection intersection becomes an ellipse; in Figure 6 the vertical projection illustrates the intersection in the plane through the lightning rod. The elliptic solutions leave regions along the base of the rectenna unprotected. Hence, the parabolic solutions of Figure 8 and the table (Fig. 9) represent maximum protection capabilities of the cone of protection with the panel scale protection configuration. The small ellipse in Figure 11 shows the cone of protection intersection for $\alpha = 40^0$, $\beta = 45^0$, and L = 0.74m.

2.2 Lightning Rod Protection at the Bay or Billboard Scale

In this system a longer lightning rod is placed at the center (or end) of each bay or billboard making them 14.69m apart. The mathematical description here is identical to that for the panel scale system (2.1). Only sizes are different. Figure 10 illustrates the billboard scale system.

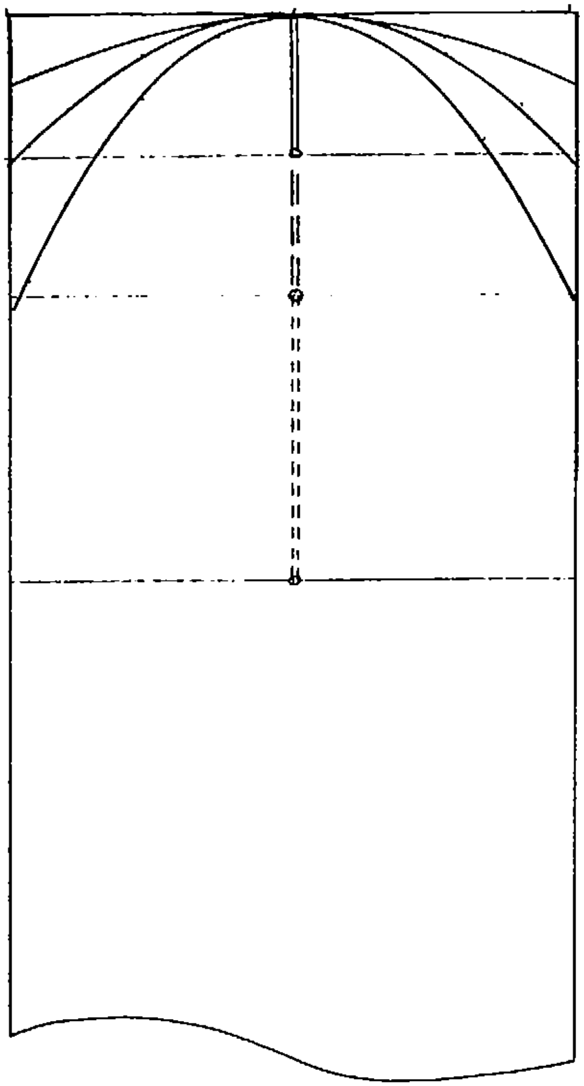


FIGURE 8

THE INTERSECTION OF THE CONE OF PROTECTION WITH A RECTENNA PANEL (THE CURVED LINES) SHOWN IN THE PLANE OF THE PANEL. LIGHTNING ROD LENGTHS = ¼, ½ AND 1 TIMES THE PANEL WIDTH ARE SHOWN PROJECTED VERTICALLY ONTO THE PANEL.

PARABOLIC TYPE SOLUTIONS

ROD LENGTH IN METERS	UNPROTECTED AREA IN %	UNPROTECTED AREA X ENHANCEMENT FACTOR
.185	1.1%	2.9%
.37	.55%	1.5%
.74	.28%	.74%

FIGURE 9

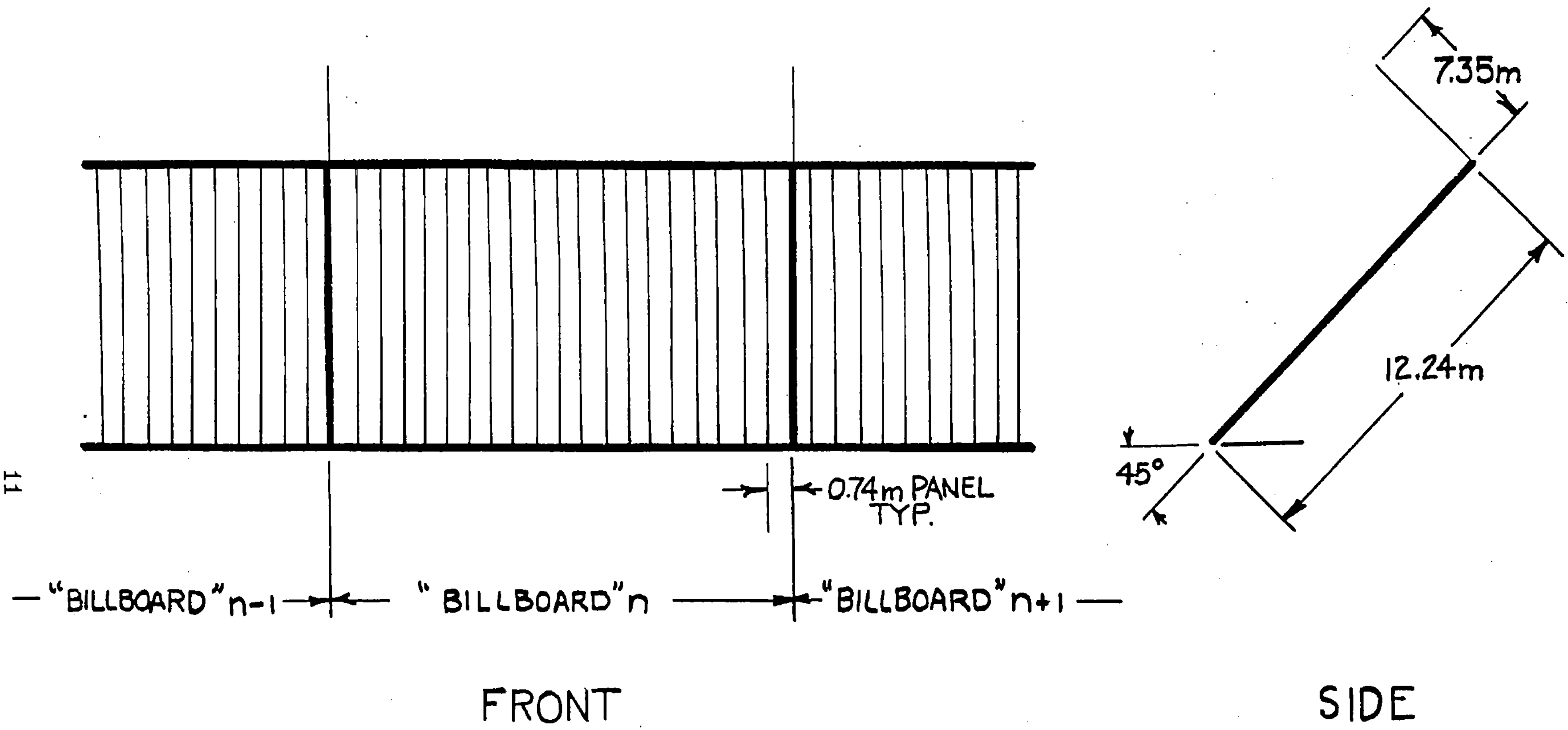


FIGURE 10

BILLBOARD SCALE LIGHTNING PROTECTION SYSTEM

To illustrate the cone of protection concept for this configuration we use as an an example, $\alpha = 40^0$, $\beta = 45^0$, and L = 7.35m (= 1/2 billboard width). The resulting intersection is a portion of an ellipse and is shown on Figure 12. Even if these long (7.35m) lightning rods were placed every 14.69m, a significant fraction of the rectenna (6.7% or when weighted by enhancement factor 18%) is unprotected (i.e. is not inside a cone of protection).

Furthermore, there are serious mechanical problems associated with supporting these long (i.e., over 22 feet) lightning rods. We think these examples are sufficient to demonstrate that configurations employing fewer lightning rods at longer spacing decreases protection and creates structural problems that ultimately will increase the total materials requirement.

For example, if we were to increase the length of the lightning rod in this configuration to the point that it could offer protection to the billboard in front of the one on which it is mounted (i.e. to the south), then with the appropriate phasing of rods between rows of billboards we could get total protection in the cone of protection context. The length of the rods would need to be 12m in order to provide this coverage.

2.3 The Distributed Lightning Protection System

The distributed lightning protection approach replaces the many lightning rods with a continuous horizontal conducting structure, as depicted in Figure 13. The region of protection now becomes the volume beneath two planes whose intersection is the horizontal protecting structure. This protection tactic is essentially the one employed by the power transmission companies. The angle between the protecting planes and vertical is variable; 45° is thought to be adequate but some designs use 30° for extra protection. This line is called the "static" by the power companies and this term is used here for convenience.

Figures 7 and 8 provide the correct geometric considerations for the distributed lightning protection if we interpret the end point of the lightning rod to be the location of the static. We note that the figures apply anywhere along the rectenna, not just in the specific locations required by the lightning rod analysis.

For consistent comparisons with the other lightning rod systems we will use $\alpha = 45^0$. Since $\alpha < 45^0$ for rectennas below 40° latitude, the top edge of the rectenna is protected by the static for any value of L, the displacement distance. If we try to use a smaller, more conservative value for β, we will run into problems in protecting the top edge of the rectenna with any system tht does not cast a radio shadow on an active rectenna surface. The design constraint that we will use to specify L will be that the southward plane of protection intersect the rectenna surface at the base. Therefore,

$$L = 12.2\text{m} \tan (45^0 - \alpha).$$

For α in the range 45° to 30°, L has the range of values 0m to 3.3m. This simple analysis ignores the protecting capability of the immediate southward row of the rectenna on the base of the row being considered. When these additional protective effects are considered we find that:

$$L = 6.1\text{m}\,(1 - \tan\alpha)$$

For α in the range 45^0 to 30^0, L now has the range 0m to 2.6m.

Figure 13 gives the configuration of the distributed lightning protection system for $\alpha = 30^0$, which represents the most difficult situation to protect. In this situation the static is displaced by 2.6 meters from the top edge of the rectenna; note that the 45° planes of protection provide total coverage of the rectenna.

We wish to emphasize that the set of horizontal statics not only provide total protection in the sense that lightning flashes are expected to hit the statics instead of the active rectenna surfaces but that this system also reduces the induced voltages and currents in the rectenna. We estimate that induced charges, currents, and potentials are reduced by 1/2 by the static protection system.

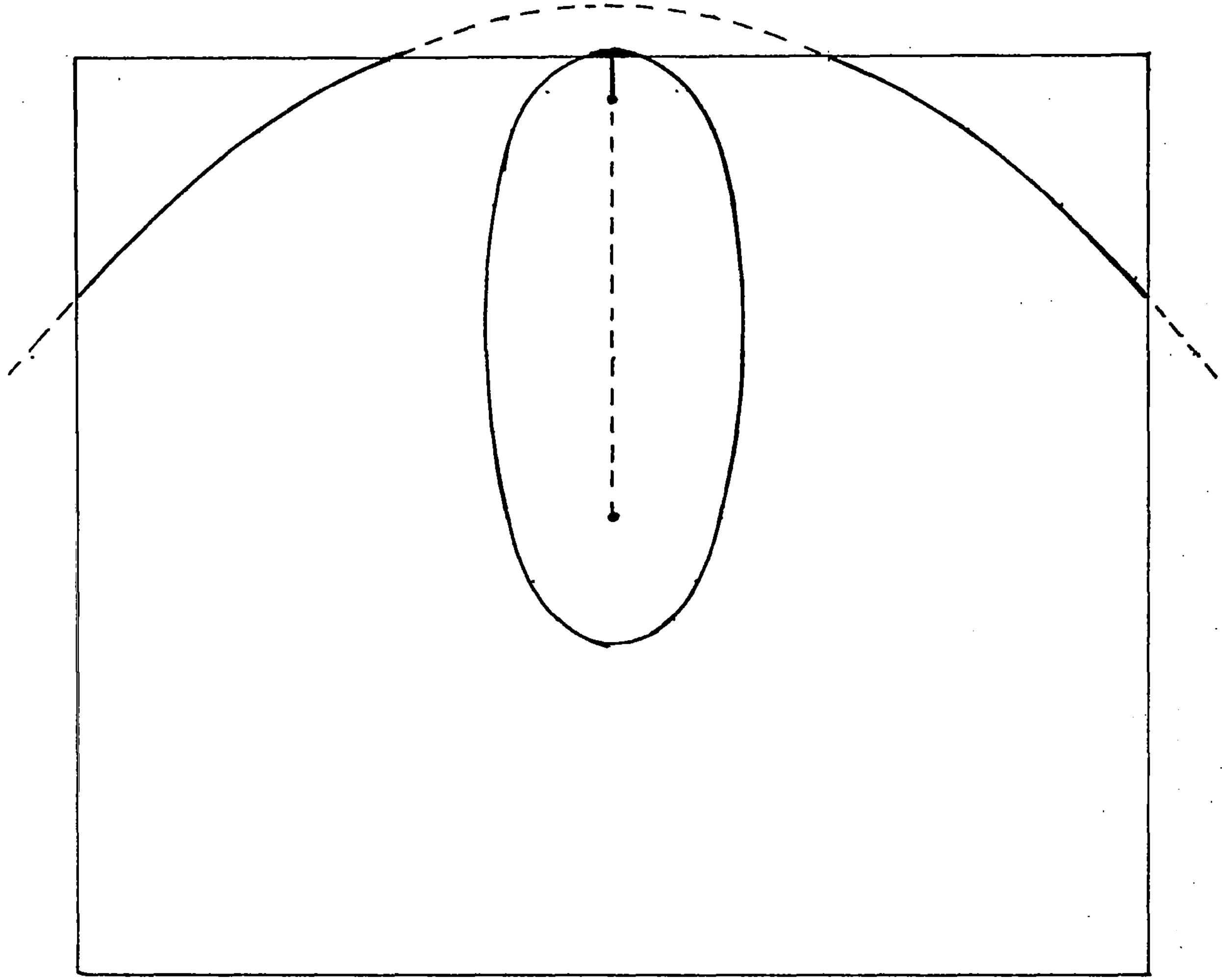


FIGURE 11

PANEL SCALE PROTECTION COMPARED TO BILLBOARD SCALE PROTECTION SHOWN AS IN FIGURE 8 EXCEPT HERE ON A BILLBOARD.

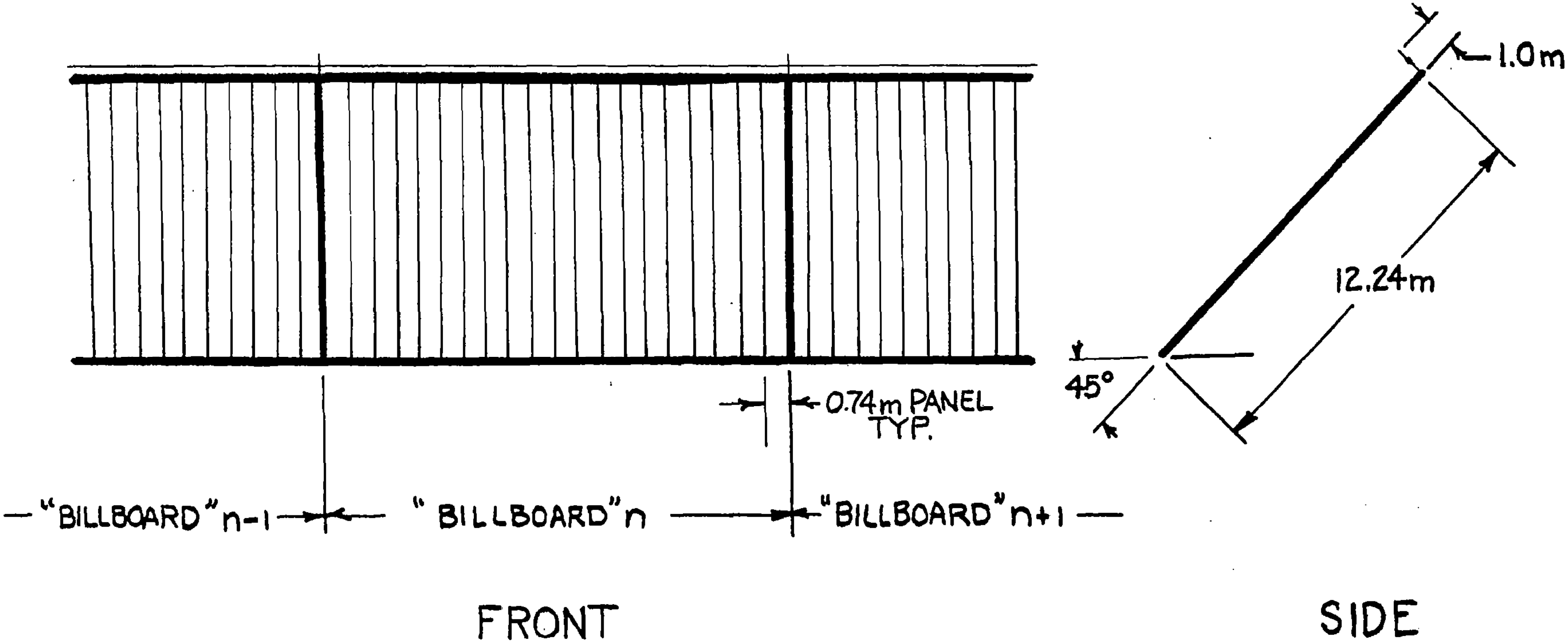


FIGURE 12

DISTRIBUTED LIGHTNING PROTECTION SYSTEM

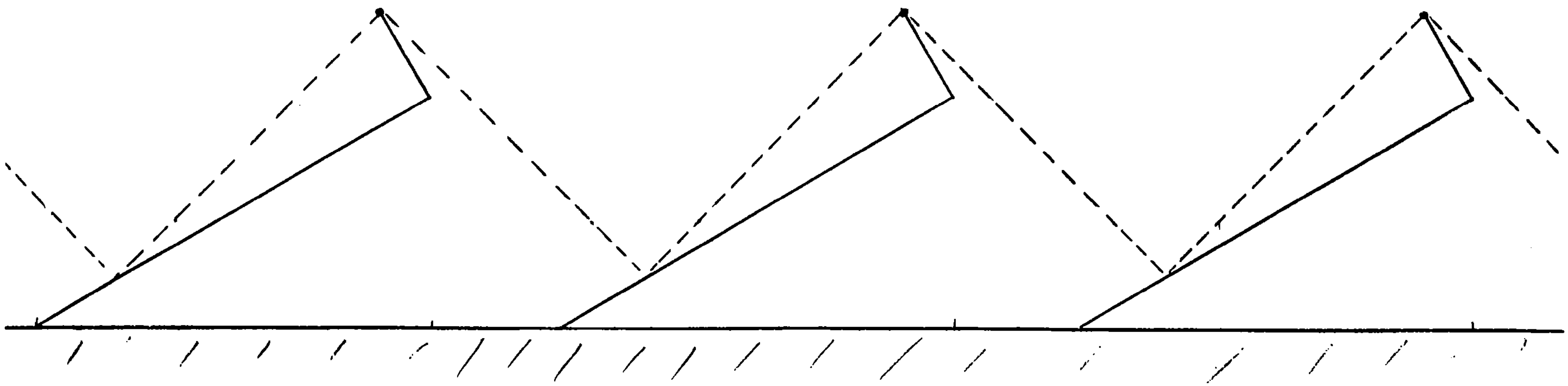


FIGURE 13

DISTRIBUTED LIGHTNING PROTECTION SYSTEM
ILLUSTRATING FORWARD AND BACKWARD PRO-
TECTION FOR SMALL INCLINATION ANGLES

II. SIMULATIONS OF LIGHTNING STRIKES TO THE SPS RECTENNA WITH AND WITHOUT PROTECTION

A series of experiments were performed in our electrostatic test chamber with a scale model of the SPS rectenna. The experiments consisted of exposing the model rectenna to a series of high voltage discharges produced with a Tesla coil.

The strikes to the rectenna were photographed using time exposures in a darkened room. A wire from the upper plate conducted the discharge to the vicinity of the model rectenna and provided us with a limited control over the area of the strike. This allowed us to keep the strikes near the volume in focus by the camera.

Different areas of the model rectenna were protected by different systems, and one area was unprotected. The following paragraphs describe samples of these experiments:

1. The Unprotected Rectenna

Most of the strikes were to the upper edge of the billboard because of the larger enhancement factor at that point. Several strikes to the billboard face occurred.

In Figure 14, we see two strikes to the unprotected billboard section, one of which is to the billboard face. Notice that these strikes are perpendicular to the face when near the face; we would anticipate this because the equipotential lines are nearly parallel to the face here.

In Figure 14, we also see for comparison the three lightning protection systems modeled. To the left is the billboard scale system; to the right is the panel scale system; and behind the flashes is the distributed lightning protection system.

2. The Panel-Scale Protection System

The next three figures are examples of strikes photographed on the section of the model rectenna that was protected by the panel-scale lightning protection system.

In Figure 15, we see two strikes on the same billboard, both of which terminate on the panel-scale lightning rods.

Figure 16 shows two strikes from a different view going to two different billboards. The panel-scale protection system here is seen to protect only the front billboard. Protection is probably greater for real lightning because in our experiments we artificially bring the "leader tip" very close to the billboard with the wire.

Multiple strikes to the panel-scale protection system are seen in Figure 18. One of the strikes goes directly to the billboard face. this type of failure will occur in nature, but with lower probability than illustrated here.

3. The Billboard-Scale Lightning Protection System.

Two sets of experiments were made with the billboard-scale lightning protection system. The one illustrated in Figure 19 corresponds to rods of length 7.35m. (A second series of strikes were made with rods cut to one-half of this length, but these were photographed in color and are not suitable for this report.) Figure 19 illustrates the capability of these long rods to direct lightning to the desired point.

In Figure 20, we have a side view of a billboard-scale protector taking a strike and protecting the billboard-face. Figure 21 illustrates the "hole in the armor" of the billboard-scale lightning protection system. Two flashes strike the protection system, but a third strikes the billboards between two protectors, as predicted in Figure 12. With real lightning this is less likely to happen, but it can and will occur.

4. The Distributed Lightning Protection System.

The displacement distance of the static from the billboard was scaled from 0.74m to make it correspond to the height of the panel-scale protection system. Fewer failures-to-protect were observed with this system but they did occur. With real lightning, they would be even less likely to occur.

In Figure 22, we see two strikes to two different billboards from the side view. Figure 23 shows two strikes to the same billboards, which were rovided with a distributed lightning protection system. One strike is to the terminal support rod at the billboard edge, which is the preferred point of strike. The other strike goes to the horizontal static line between the terminal support rods.

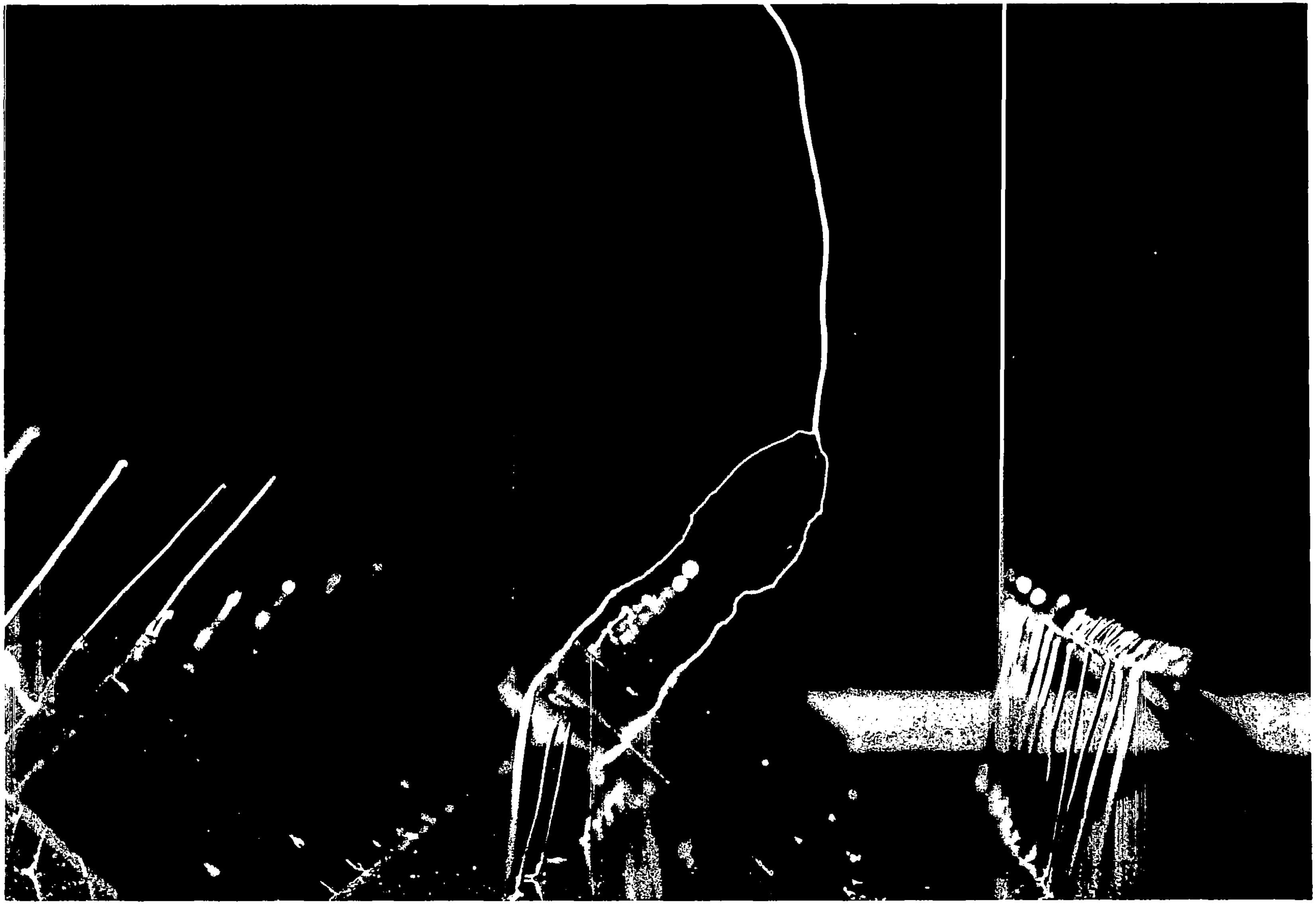


FIGURE 14

FIGURE 15

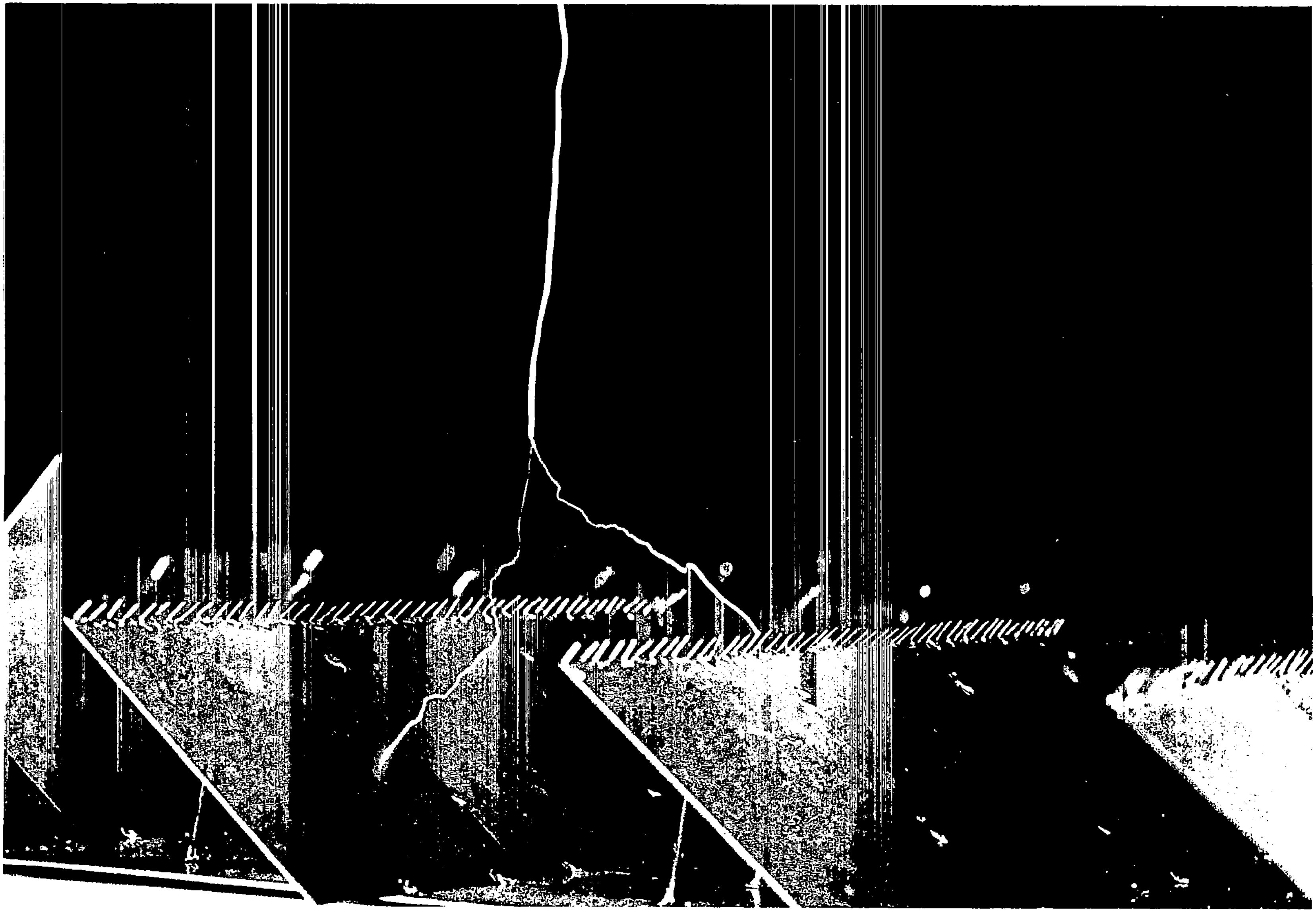


FIGURE 16

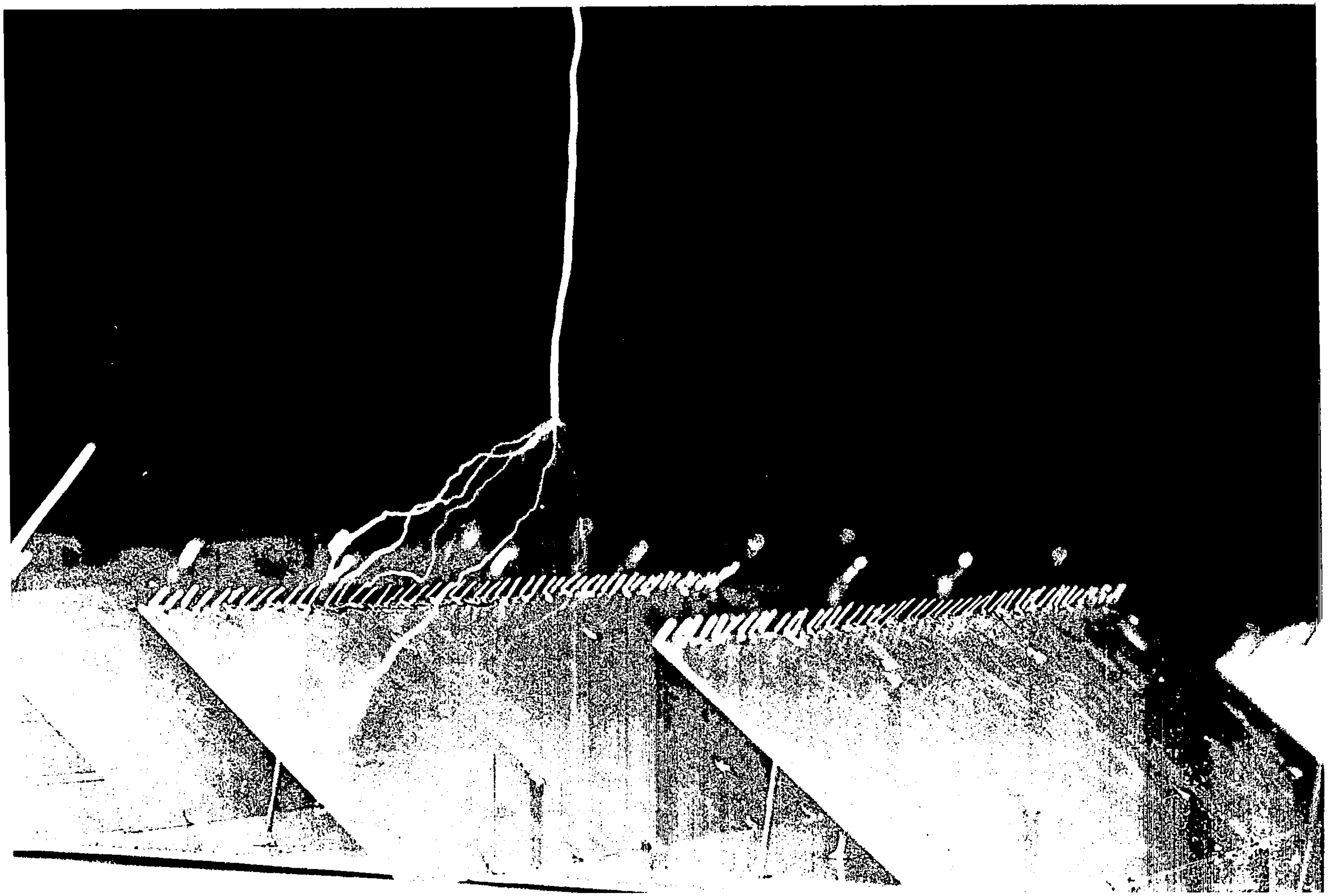


FIGURE 17

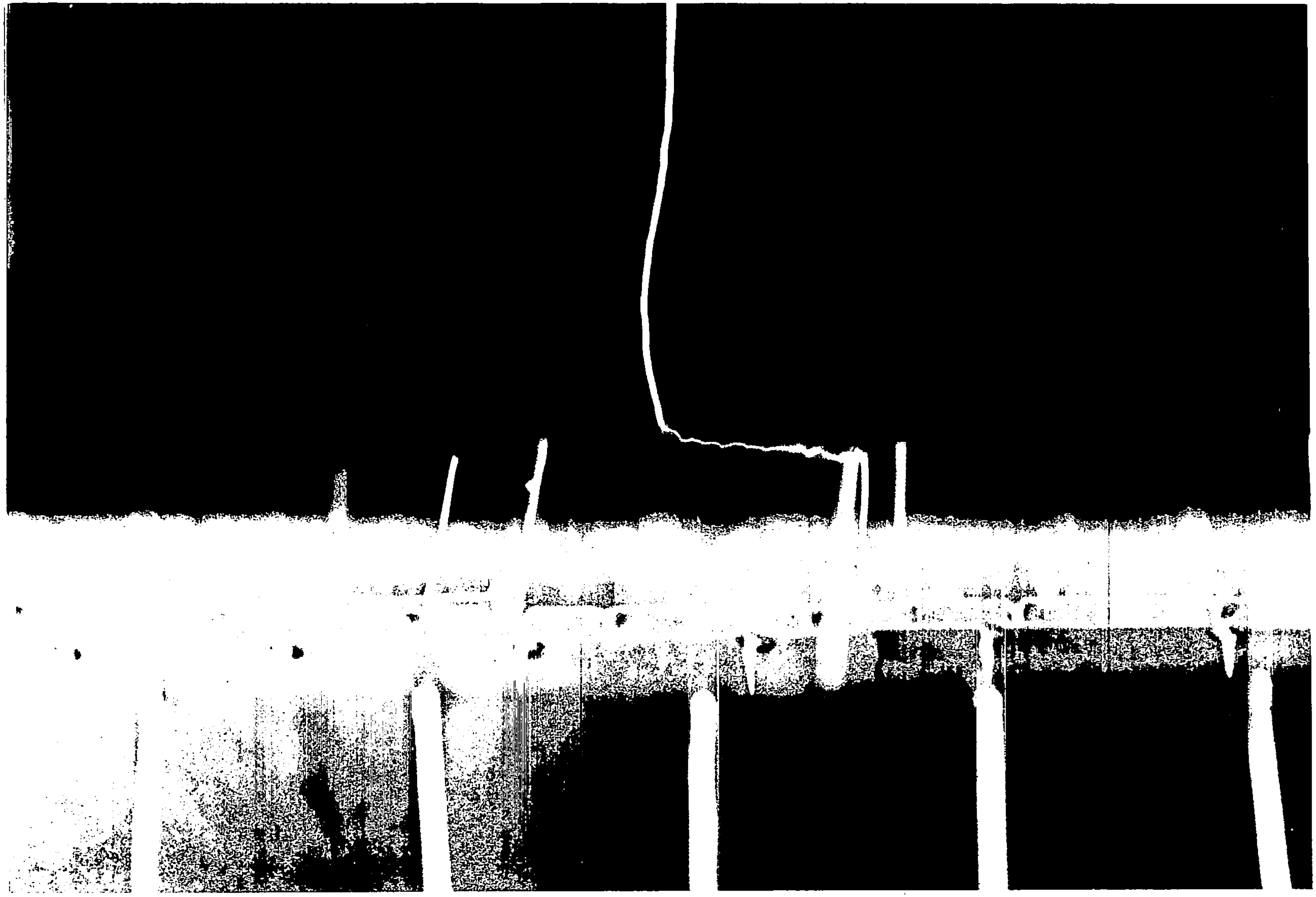


FIGURE 18

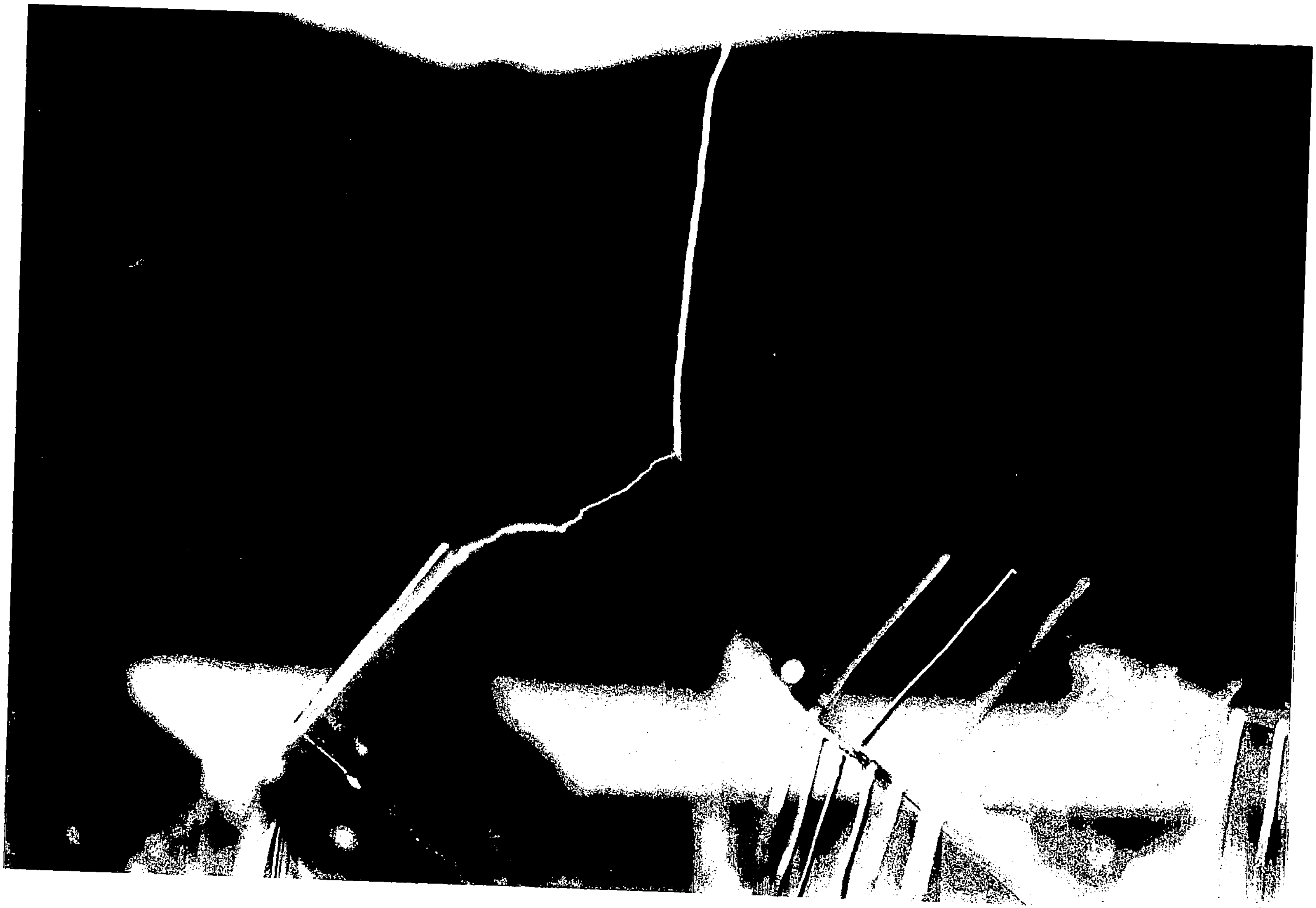


FIGURE 19

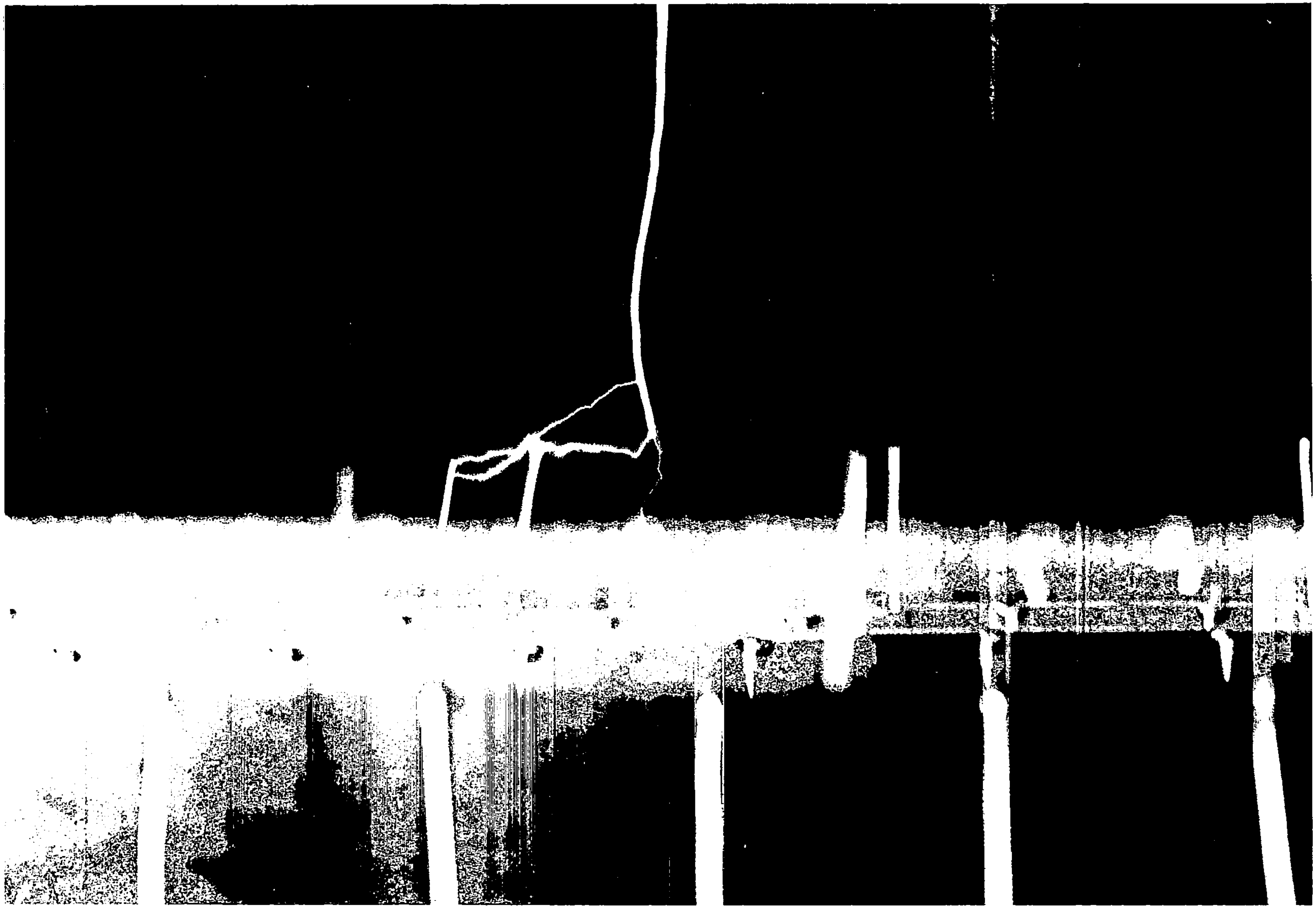


FIGURE 20

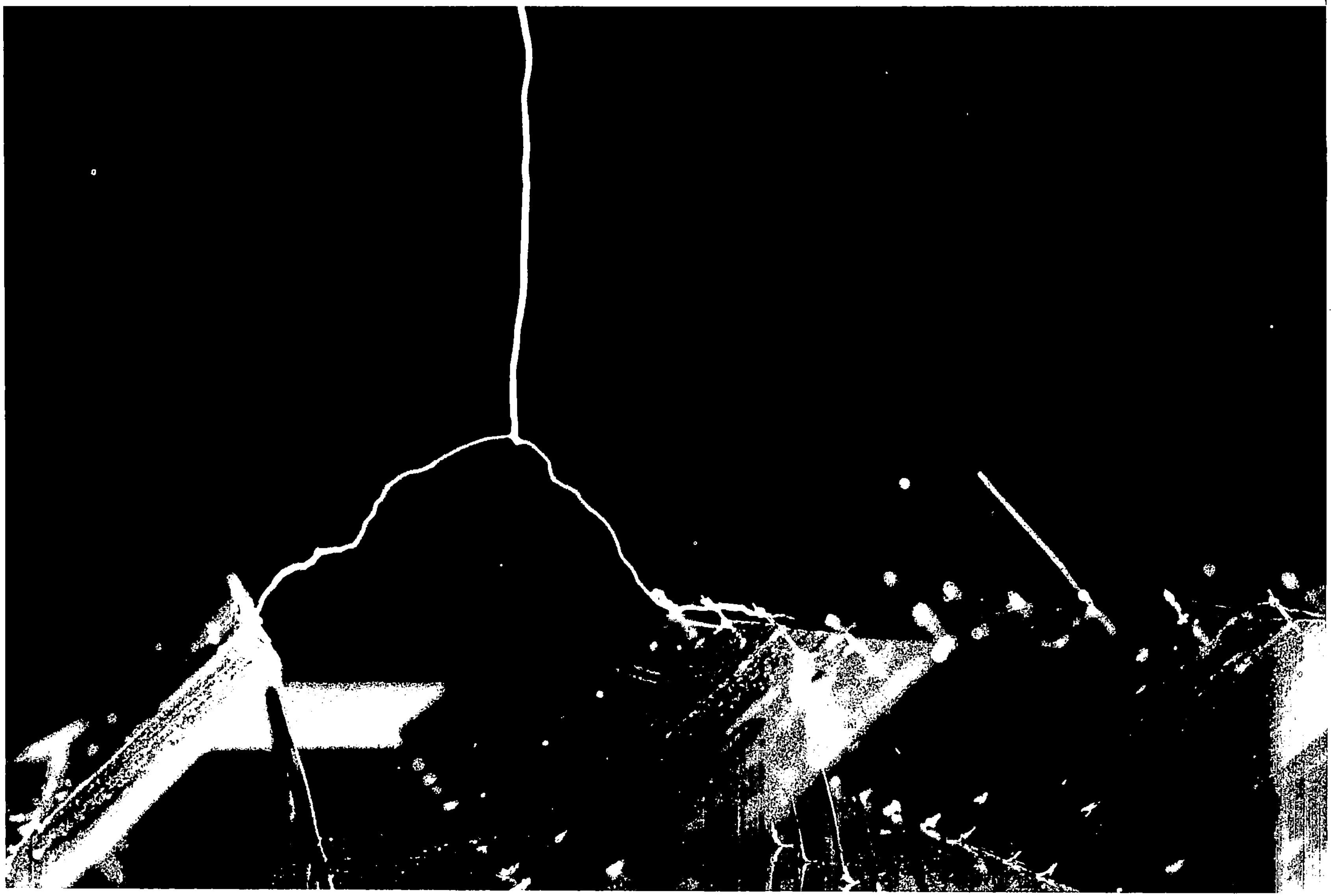


FIGURE 21

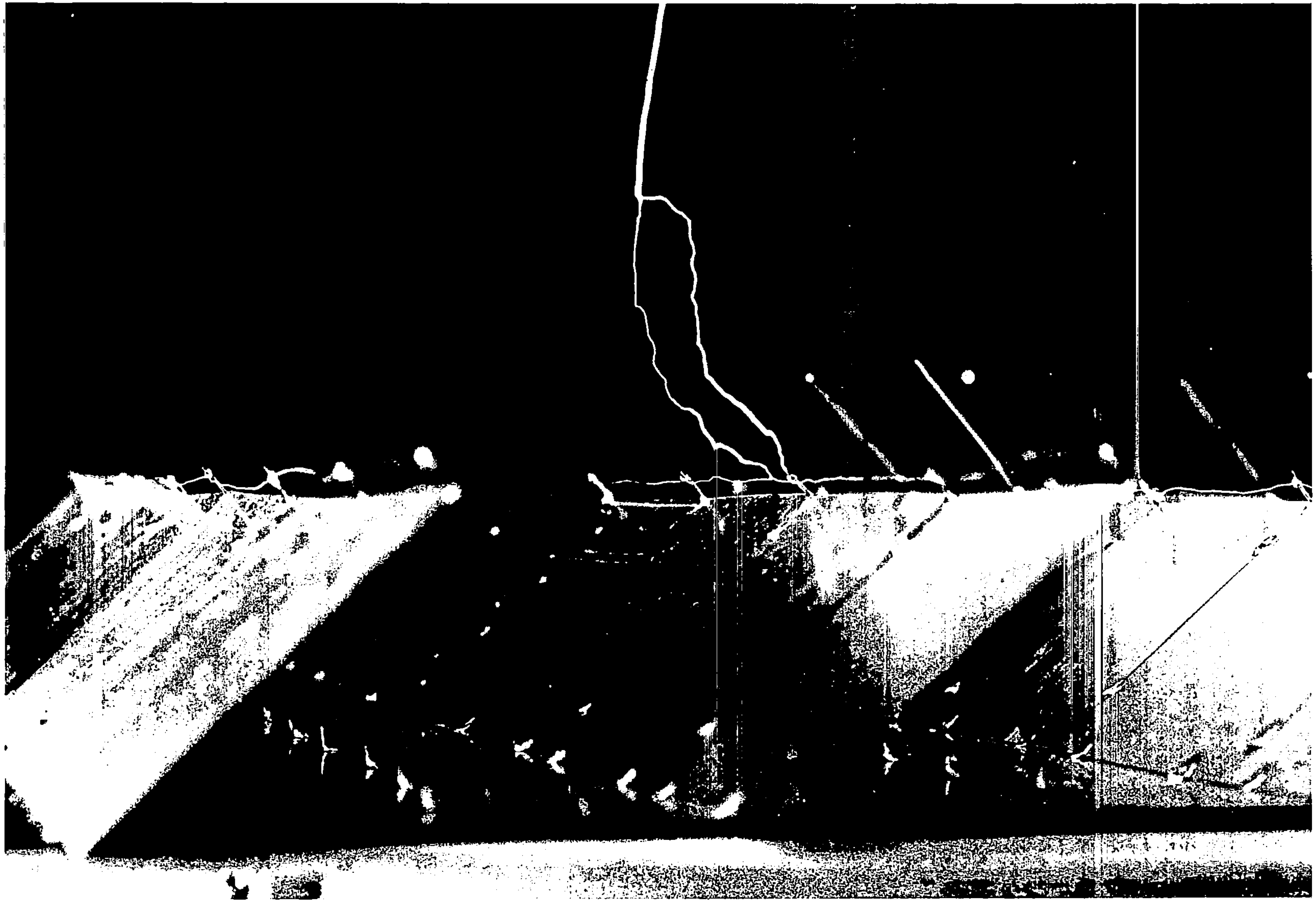


FIGURE 22

III. GROUNDING CONSIDERATIONS FOR THE PROPOSED LIGHTNING PROTECTION SYSTEM

The thundercloud charges induce a large surface charge on the rectenna below the cloud; during the stepped leader period even larger surface charges are induced on the region below the leader tip. Most of the current flowing during the return strokes of the lightning flash must be distributed by the grounding system to connect with the induced surface charges. If adequate paths for these currents are not planned and provided, the lightning will make its own paths. Most of the induced surface charge will reside on the horizontal statics of the recommended distributed lightning protection system. The primary grounding system described here is to provide low impedance paths for the redistribution of the induced surface charges and the part of the lightning charge that resides on the rectenna surface.

1. Primary East-West Grounding

It is absolutely necessary that the horizontal statics have a good low impedance connection at billboard edges. The static should appear to be a continuous very low impedance conductor in the east-west direction, as illustrated in Figure 24.

2. Primary North-South Grounding

It is also necessary that the statics are mutually grounded in the north-south directions; there are two methods of achieving this:

2.1 Periodic connections north-south at the level of the statics. If these north-south statics are aligned along the billboard edges, then there will be little power loss due to microwave shadows (See Figure 24.)

2.2 Interconnect grounding in the north-south direction at the surface or sub-surface level (see figure 25) can also be used, but this approach creates a higher impedance to north-south currents on the static system.

2.3 A surface level grounding network is required in addition to the primary static grounding network. The surface network must handle the redistribution of induced charges on the rectenna surfaces and power distribution systems and it provides a safe working environment at the surface level. East-west continuity with low impedance connections must be provided at the base of the rectenna support structures, and north-south continuity with low impedance connections as discussed in 2.2 and illustrated in Figure 25 must be provided. Figure 26 highlights the surface level grounding network.

2.4. Interconnections between the primary and surface grounding networks should be provided by the vertical conductors located at every billboard upper corner; these are the same structures on which are mounted the terminals and supports for the statics. The vertical interconnections are highlighted in Figure 27.

2.5 The ultimate or final component of the grounding system is the tie-in to Earth ground. At regular intervals in the rectenna a deep earth grounding rod must be driven into the soil to make good contact with a conducting soil for earth ground28

The organization of the earth grounding system should be along diagonals, as illustrated in Figure 28. Here we see that the placement of earth ground at every fourth billboard but on a diagonal produces a grid such that lightning striking the primary grounding network will never have to travel more than 30 meters along the east-west conductors before finding a ground, or 32 meters along the north-south conductors (for a rectenna with a 40° inclination angle).

THE PRIMARY GROUNDING SYSTEM AT THE STATIC LEVEL

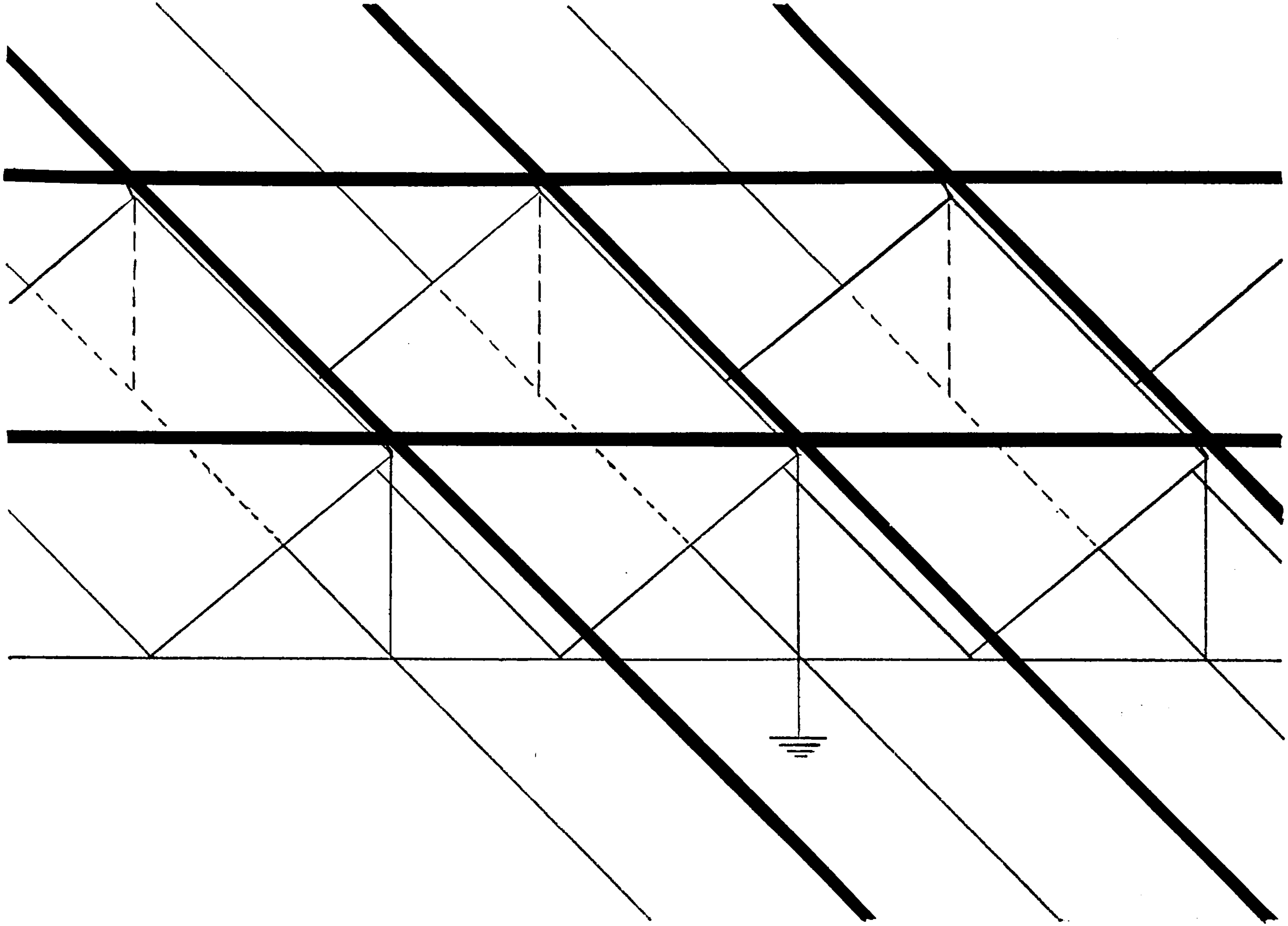


FIGURE 24

GROUNDING
RECTENNA LIGHTNING ROD SYSTEM

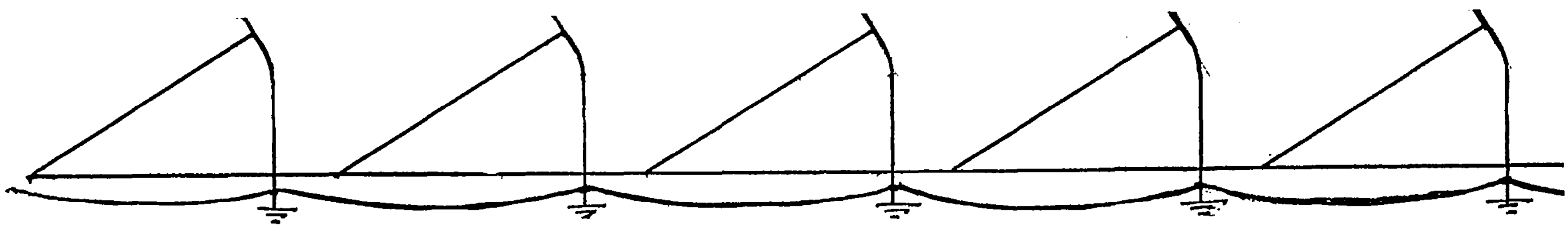


FIGURE 25

THE SURFACE-LEVEL GROUNDING NETWORK

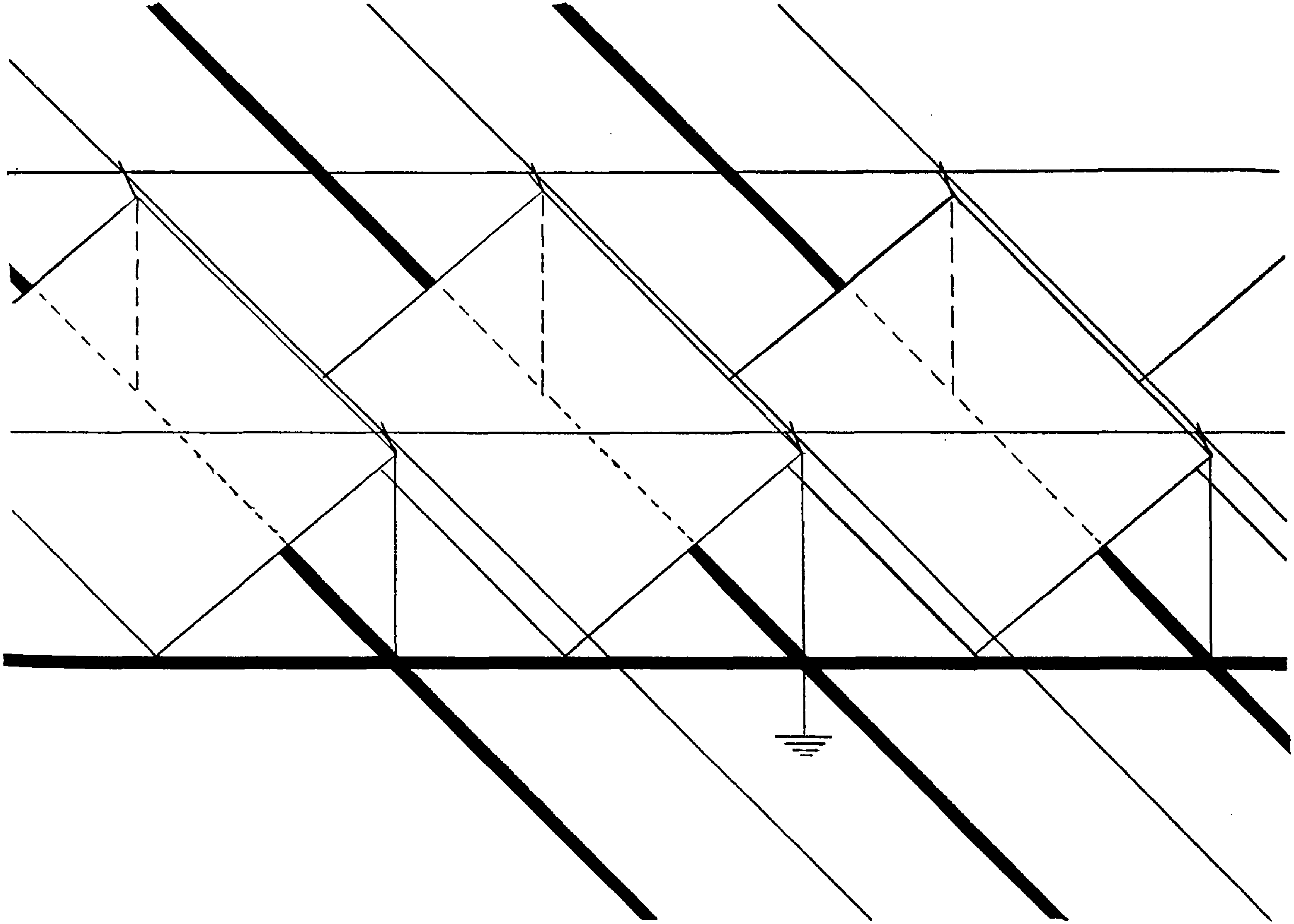


FIGURE 26

VERTICAL INTERCONNECTIONS BETWEEN PRIMARY AND SURFACE NETWORKS AND ON EARTH GROUND

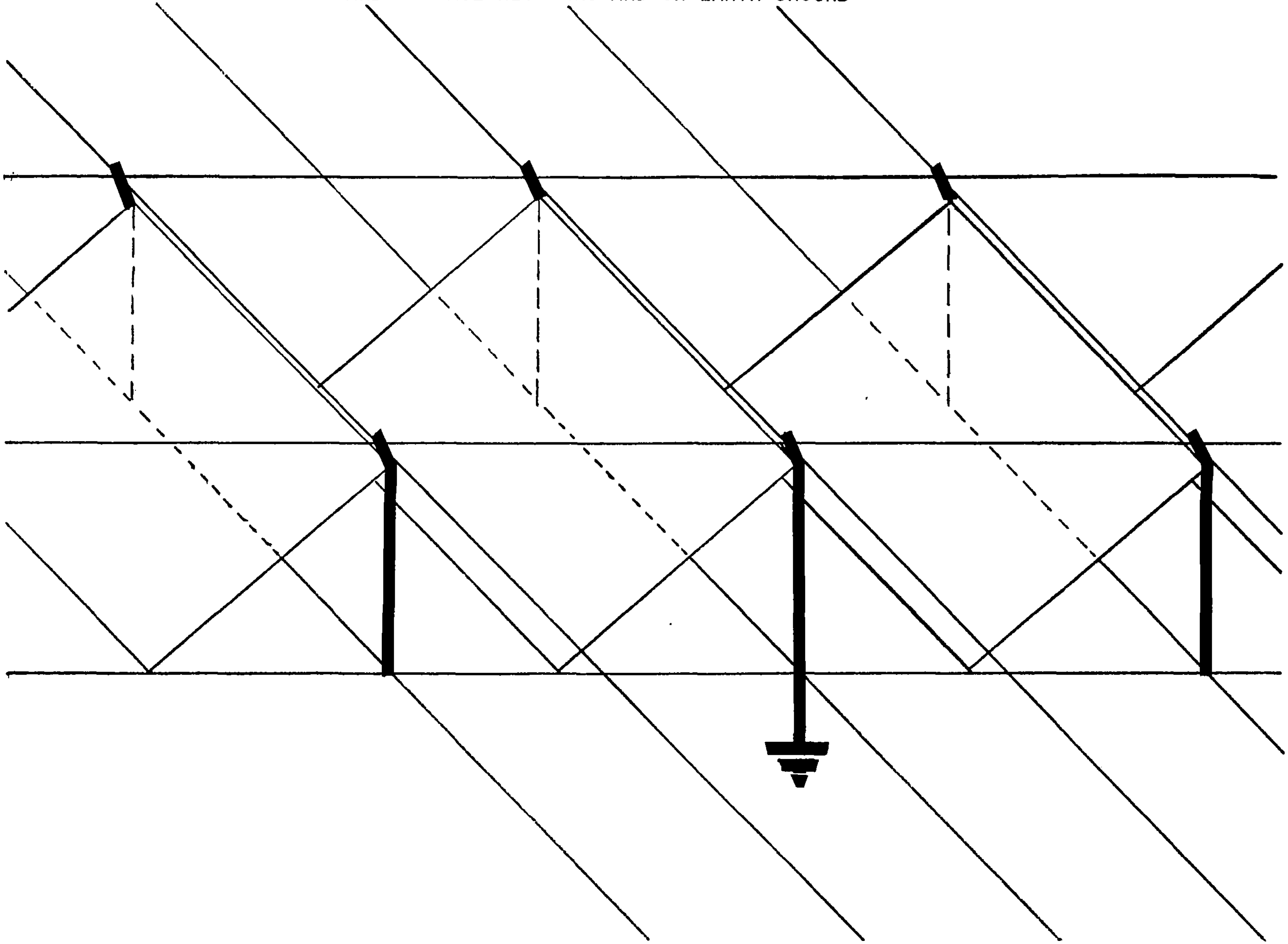


FIGURE 27

Placement of Earth Grounds

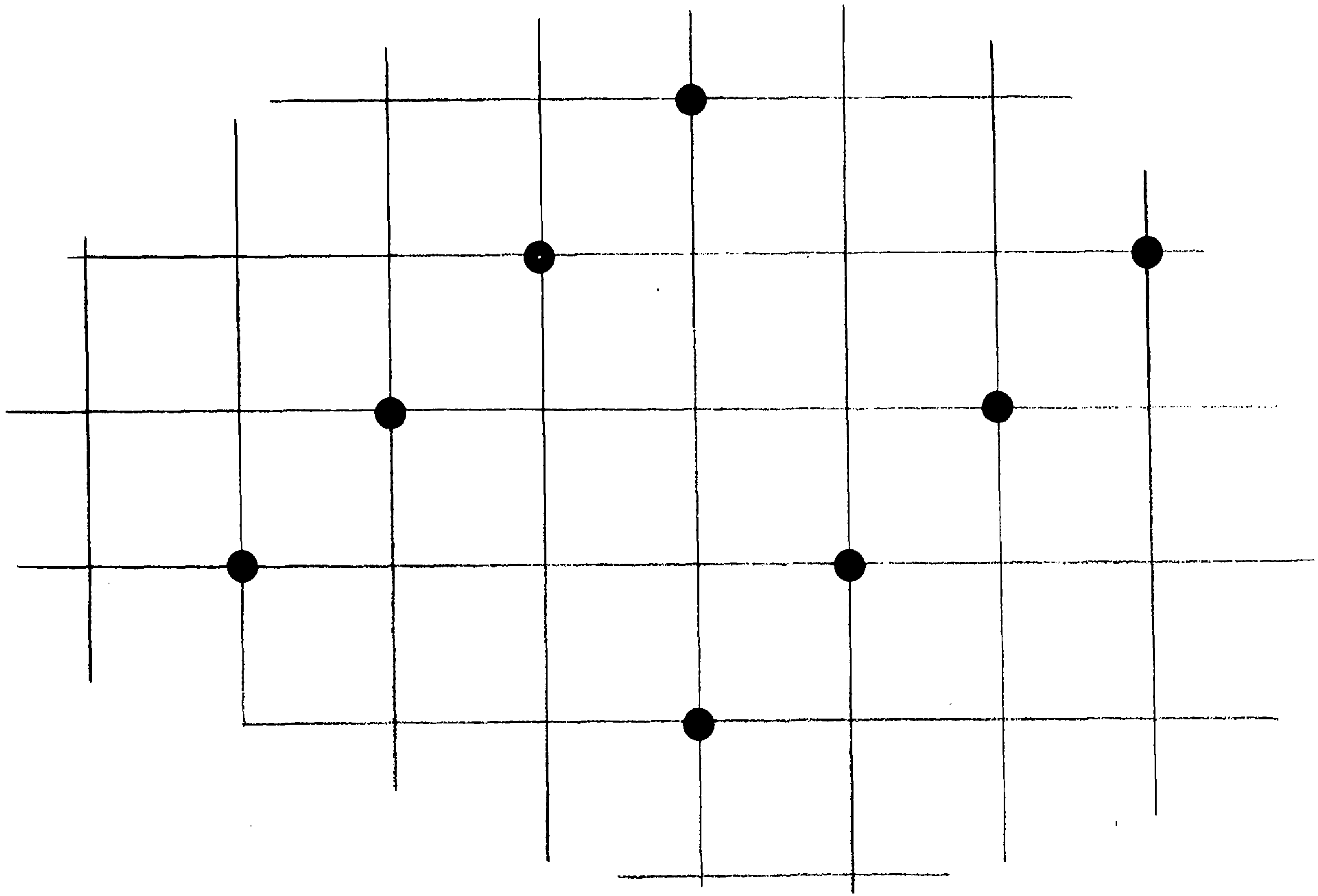


FIGURE 28

IV. MATERIALS AND SPECIFICATIONS FOR LIGHTNING PROTECTION

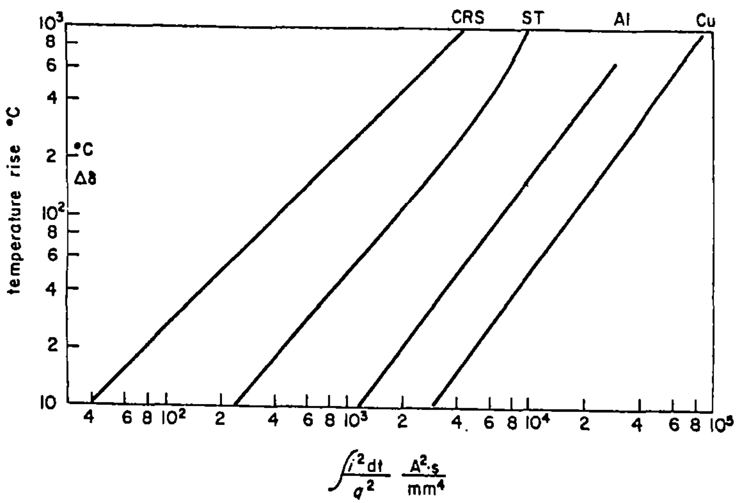
It is premature to specify the final form for the materials for the lightning protection system. We think that the system should be integrated into the structural design of the rectenna itself; in this case many other considerations are necessary in addition to the capability to conduct lightning currents. The data displayed in Figure 29 (H. Baatz, Protection of Structures, in Lightning Vol. 2, ed. by R.H. Golde) is useful for order-of-magnitude estimates of the lightning current requirements.

Example: If the design permits a 100° C temperature rise in an aluminum member carrying 10^5 Amps for 10^5 seconds, we need approximately 3 mm^2 crossectional area of aluminum material in the conductor. Note that the recommended crossections for building codes are larger (~ 80 mm^2) indicating designs for lower temperature operation plus safety margins.

The lightning conductor need not be solid. From a structural point of view a tubular or other extruded shape would be preferable. Such configurations are compatible also with the lightning protection recommendations.

Specific values of materials for wire

Material	Steel	Copper	Aluminium
Density (g/cm^{-3})	7·7	8·92	2·7
Electrical resistance (Ω mm^{-2} m^{-1})	0·17	0·0178	0·029
Heat (cal °C^{-1} g^{-1})	0·115	0·093	0·023
Melting point (°C)	1,350	1,083	658



Temperature rise of conductors as function of current square impulse per cross-section square; Cu = copper, Al = aluminium, ST = steel, CRS = corrosion-resistant steel.

Cross-section for lightning conductors

Installation components	Material	Cross-section (mm²)	Dimension: Rod (mm, radius)	Dimension: Strip (mm × mm)
Air termination	Steel, galvanized	50 (25)[a]	8	20 × 2·5
Rods up to 0·5 m long	Steel, stainless	110	12	30 × 3·5
Down conductors	Copper	50 (16)[a]	8	20 × 2·5
Conductors in ground	Aluminium[b]	80 (25)[a]	10	20 × 4
Sheet metal	Steel, galvanized			0·5 mm
	Copper			0·3 mm
	Aluminium, Zinc			0·7 mm
	Lead			2.0 mm

[a] Lowest cross-sections used in some countries.
[b] Not for use below ground.

FIGURE 29

V. ESTIMATE OF POWER LOSS FROM THE BEAM

A rough maximum estimate of the power loss from the microwave beam due to the lightning protection devices can be obtained by assuming that the microwave shadow cast by the static lightning protection system is twice the crossectional area of the devices. We assume that the conductors are 2 cm wide of 1 mm thickness tubular material, providing 60 mm^2 of crossectional area for conducting. The assumed shadow of these structures is approximately 0.6% of the rectenna area (see Figure 30.). This is a maximum estimate of the loss.

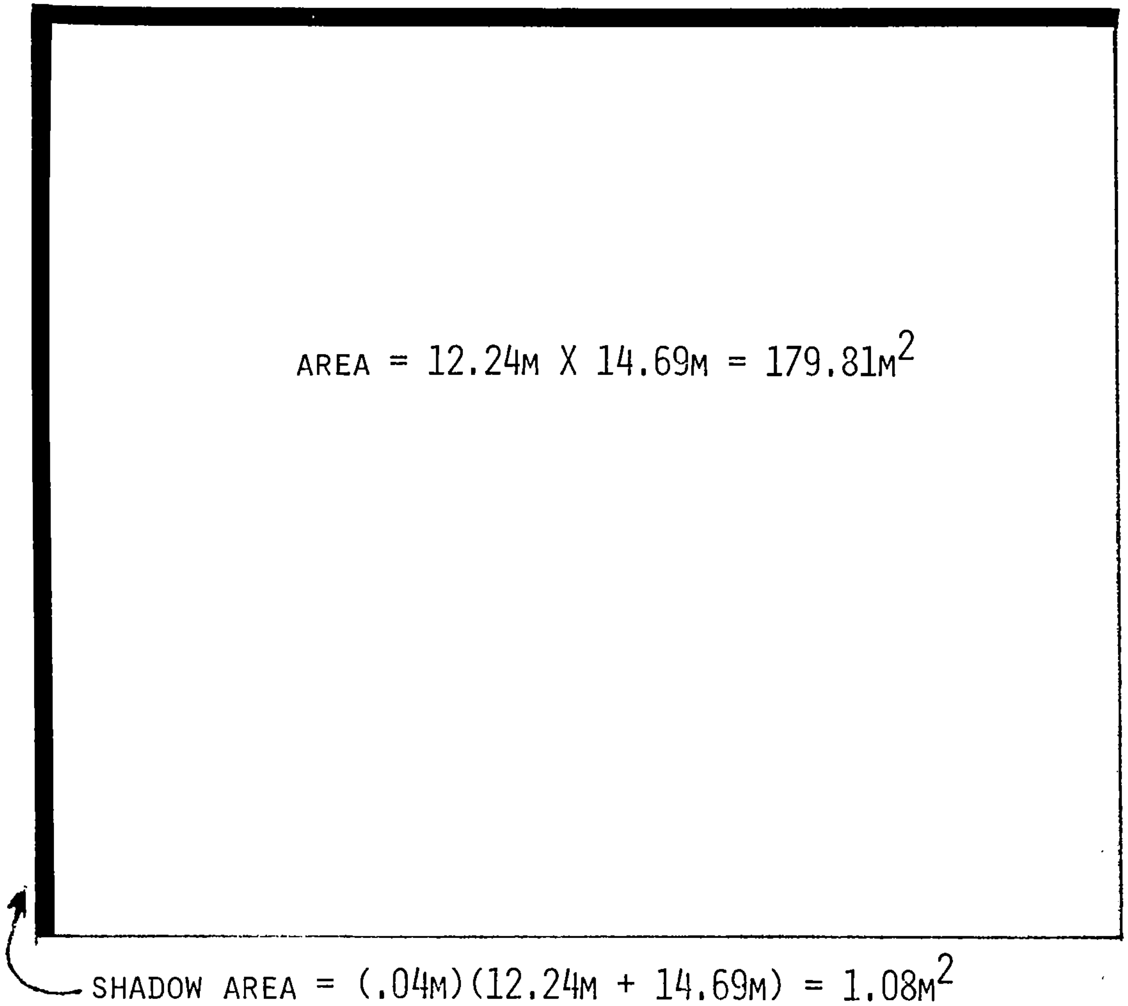

AREA = 12.24M X 14.69M = 179.81M^2
SHADOW AREA = (.04M)(12.24M + 14.69M) = 1.08M^2

FIGURE 30

VI. MICROWAVE DIODE FAILURES DUE TO INDUCED CURRENT TRANSIENTS

The 25 W S GaAs diodes used in the design of the SPS rectenna have not been produced and no failure data is available for these devices. In order to obtain estimates of failure power of the diodes in the design, we used the specification data for the HP5082-2824 microwave diode and scaled the characteristics to 25 W using the "Wunsch relationship" described in the references below. We also obtained advice directly from Dr. D.C. Wunsch regarding the extrapolated power failure current.

1. Defense Department Report D224-13042-1 EMP, Susceptibility of Semiconductor Components, dated September, 1974.

2. Defense Department Report D224-10022-1 EMP, Electronic Analysis Handbook, dated May, 1973.

3. Defense Department Report D224-10019-1 EMP, Electronic Design Handbook, dated April, 1973.

Figure 31 shows the predicted failure power for 25 watt diodes, as a function of pulse width.

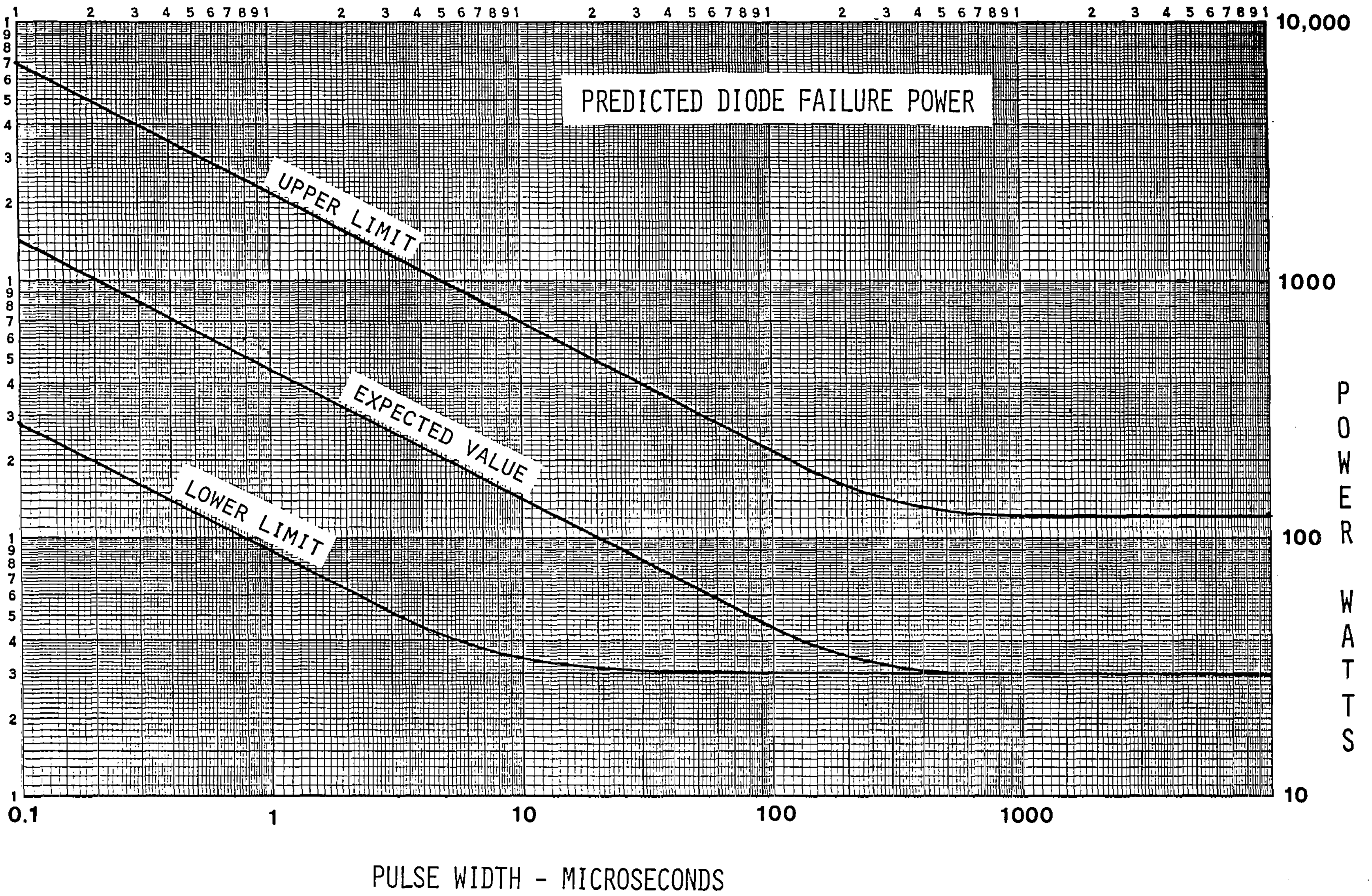

PREDICTED DIODE FAILURE POWER
UPPER LIMIT
EXPECTED VALUE
LOWER LIMIT
10,000
1000
100
10
POWER WATTS
0.1
1
10
100
1000
PULSE WIDTH - MICROSECONDS

FIGURE 31

VII. COMPUTER SIMULATION OF ELECTROSTATIC FIELD AROUND AN SPS RECTENNA

The electrostatic fields produced by the charges on the lightning channel induce charges on the rectenna and on the lightning protection conductors. Changes in this electrostatic field require a redistribution of charge on the rectenna system; the resulting currents can cause diode failure even with a lightning grounding system in place. One output of the computer simulation of the electrostatic field around the SPS rectenna is an evaluation of the induced current on the rectenna with and without the recommended lightning protection equipment.

An additional output from the computer simulation is the potential around the rectenna billboard enabling us to estimate the enhancement factors of the electric field due to the billboard shape.

The algorithm used in the simulation computes an array of values for the potential around the middle of five infinitely long billboards. We assume here that the contribution to the local potential from billboards further away is ignorably small. The surface charge distribution on the billboards is simulated with ten infinitely long line charges evenly spaced along the billboard. The value for the line charges is determined interactively with the computer to produce a zero potential contour that has the same shape as the billboard. Figure 32 illustrates this simulation.

In order to compute the potential, we will need U(x,y), the electrostatic potential at a point (x,y) in free space, where the coordinate system is such that the line of electrical charges giving rise to the potential is located at the origin. If we call the y-coordinate the height h, then U(x,H) is the electrostatic potential at x and h of a line charge λ (coulomb/meter) at a height d directly above the point x = 0. There is also a contribution to U from the image charge. Thus,

$$U(x,h) = -\frac{\lambda}{2\pi\varepsilon_0} \ln \left[\frac{x^2 + (h-d)^2}{x^2 + (H+d)^2}\right]^{1/2} .$$

From this, the potential distribution around the rectenna may be calculated. Let U(1,h) be the potential at x = 1 and y = h due to a periodic system of line charges simulating the rectenna (see Figure 31.) We then have that

$$U(1,h) = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(-\frac{\lambda j}{2\pi\varepsilon_0}\right) \ln \left[\frac{(1 - L[i-1] - X_j)^2 + (h - sX_d)^2}{(1 - L[i-1] - X_j)^2 + (h + sX_j)^2}\right]^{1/2},$$

where the free-space value for the dielectric constant is assumed and where

i = Billboard number,
j = Line charge number on billboard i,
s = Slope of billboard (= tan α),
M = Number of line charges (= 10),
N = Number of billboards (= 5).

SIMULATION OF SPS RECTENNA WITH LINE CHARGES

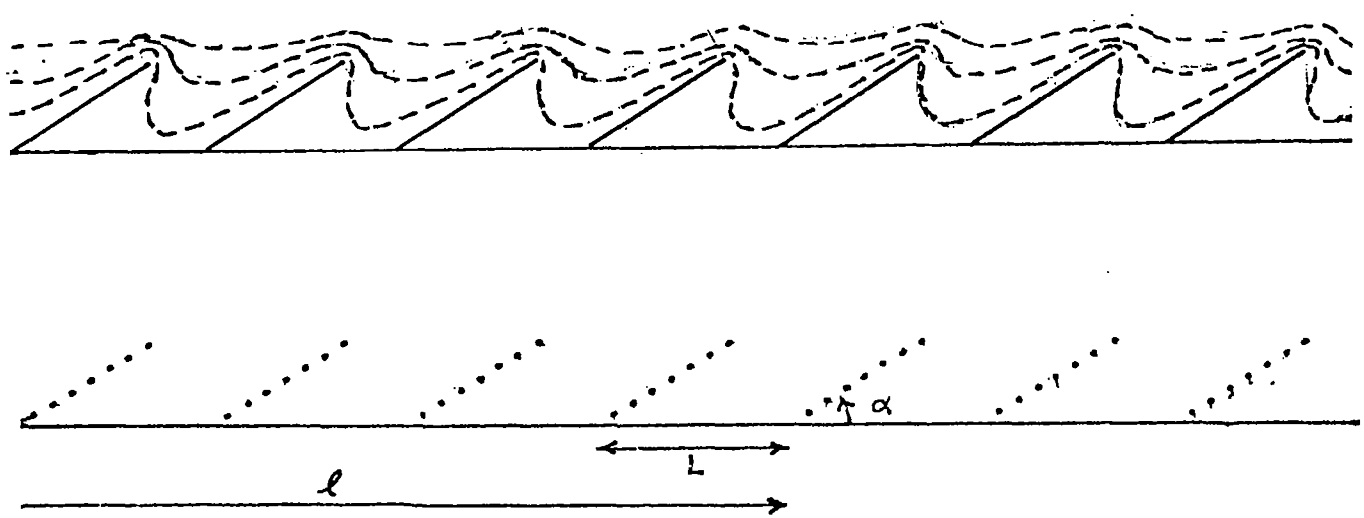


FIGURE 32

In the presence of a uniform electric field of 100,000 volts/meter (directed upward), ten line charges have been selected to produce the array of values shown in Figure 33. Three potential contours have been sketched (zero, 10,000 V, and 100,000 V) around the ten line charges on the billboard. The zero contour follows closely the position of the billboard surface, as required by the simulation algorithm. Note how closely spaced the contours are at the top edge of the billboard. Electric field enhancement factors of at least 6.5 exist in this region based upon our simulations. Higher resolution simulations would be required to refine the enhancement factor estimates.

The values obtained for the 10 individual line charges found for the solution shown in Figure 33 are (in μ Coul./m):

0.36, 0.465, 0.572, 0.679, 0.924, 1.02, 1.14, 1.78, 2.91, 4.14.

We can convert these to a surface charge density by dividing each value by the billboard distance represented by the line charge. The first line charge serves approximately 3/2 $\left(\frac{12.24\ m}{10}\right)$; the last line charge serves 1/2 $\left(\frac{12.24\ m}{10}\right)$; and all others are associated with a length $\left(\frac{12.24\ m}{10}\right)$. Figure 34 is a plot of charge/unit area (μ Coul./m^2) on the billboard as a function of length (northward) along the billboard surface.

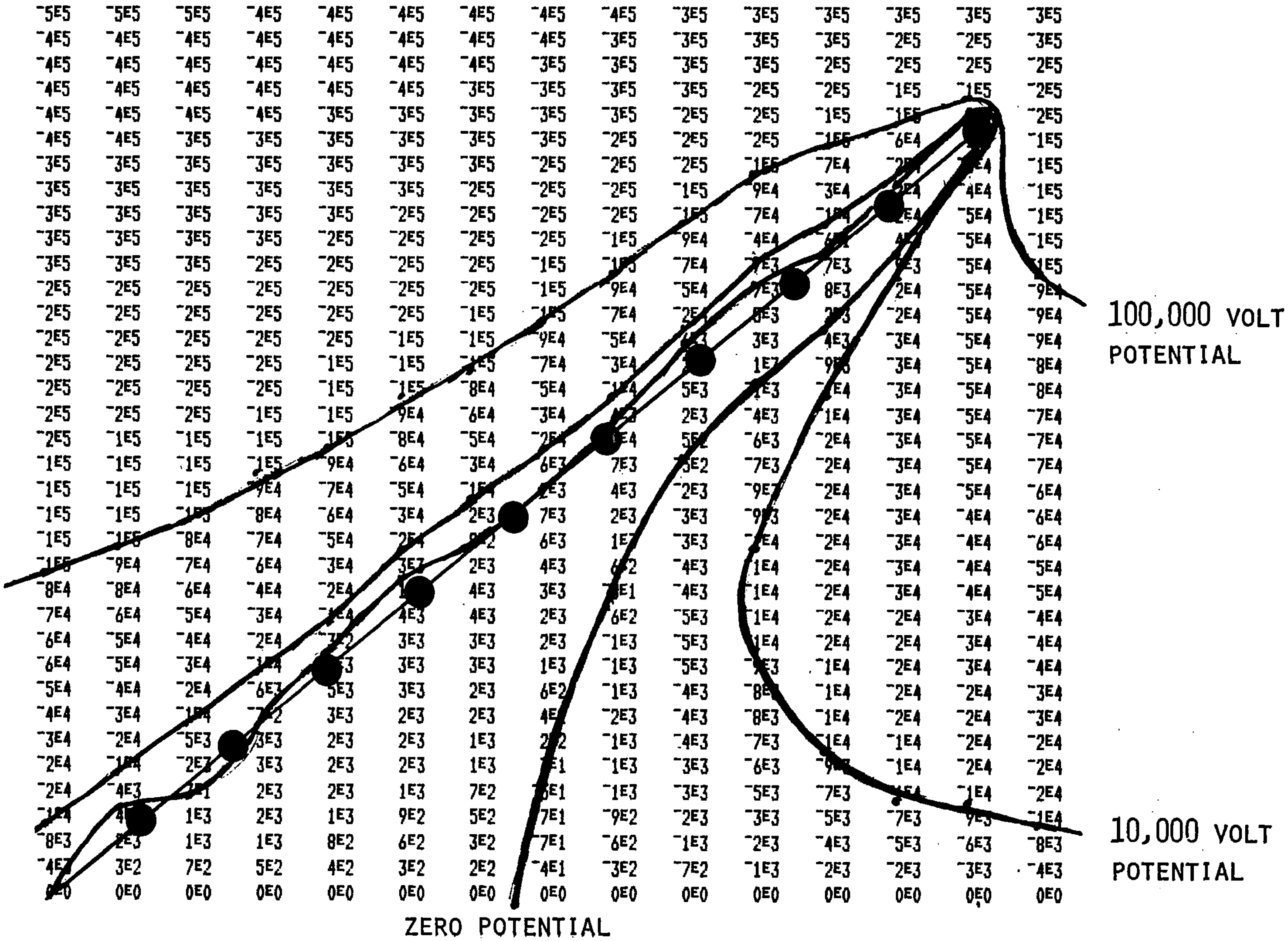
When an additional line charge in placed at the position of the lightning static, and all of line charge values are adjusted to the new configuration, we find the simulated potential function around a protected billboard - Figure 35. The placement of the static in this example is based upon the discussion in Section I.2.3., with L =0.98m, corresponding to $\alpha = 40^0$. The charge/unit length for the static is 4.6 μ Coul./m. The charge/unit lengths for the ten billboard line charges in (μ Coul./m) are:

0.315, 0.47, 0.51, 0.57, 0.87, 0.89, 0.90, 1.35, 1.78, 2.1.

These line charges may be compared with the unprotected billboard charges corresponding to the solutions of Figure 35. The protected billboard charges approach approximately one-half of the corresponding unprotected charges.

The line charges used to simulate the rectenna are normalized to a charge/unit area through division by the associated lengths, as previously described, to obtain the induced charge distribution on the protected rectenna billboard.

Figure 36 is a plot of charge/unit area in μCoul./m^2 as a function of the distance (northward) along the billboard face.



● LOCATION OF LINE CHARGES SIMULATING BILLBOARD

FIGURE 33

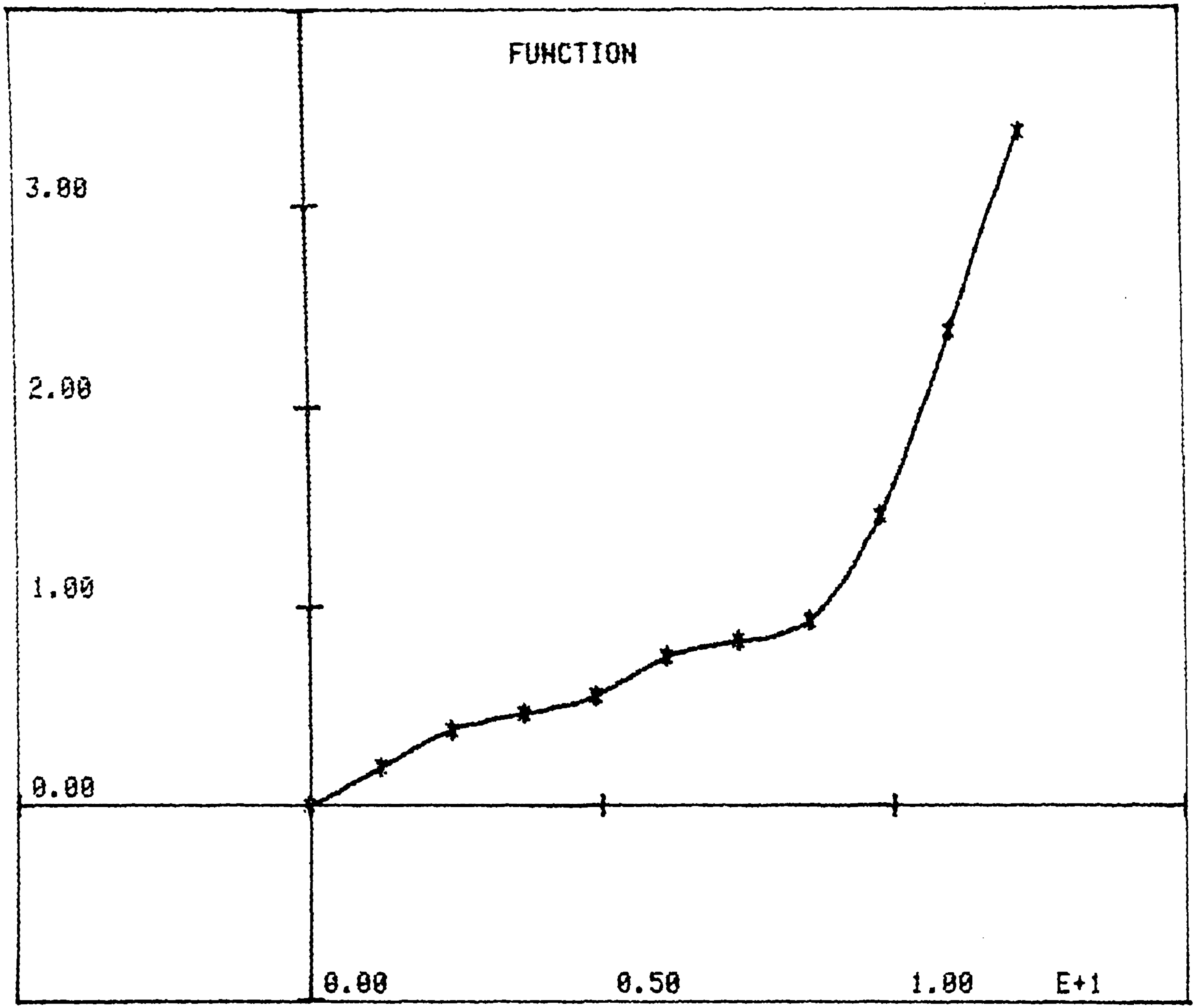
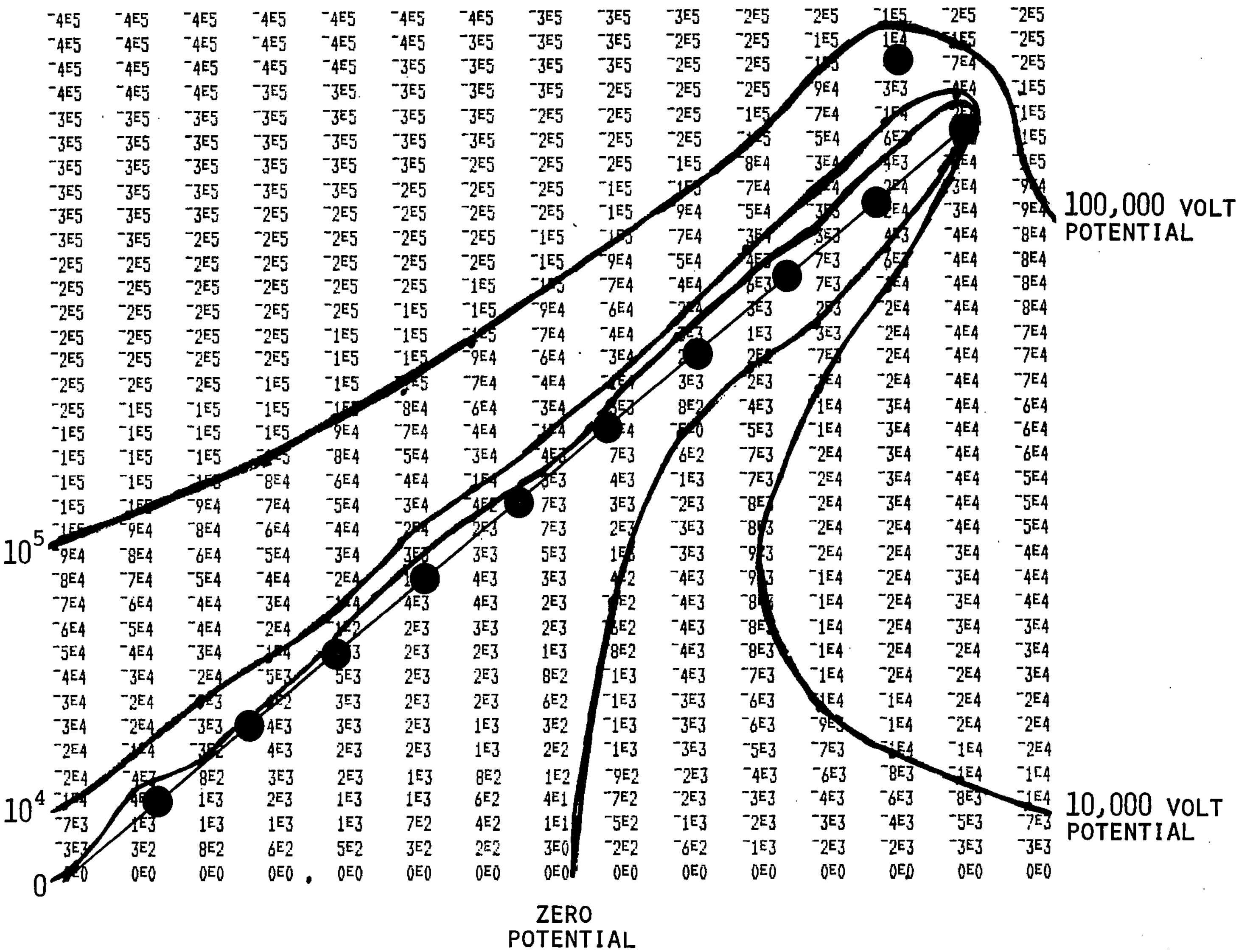


FIGURE 34



● LOCATION OF LINE CHARGES SIMULATING BILLBOARD

FIGURE 35

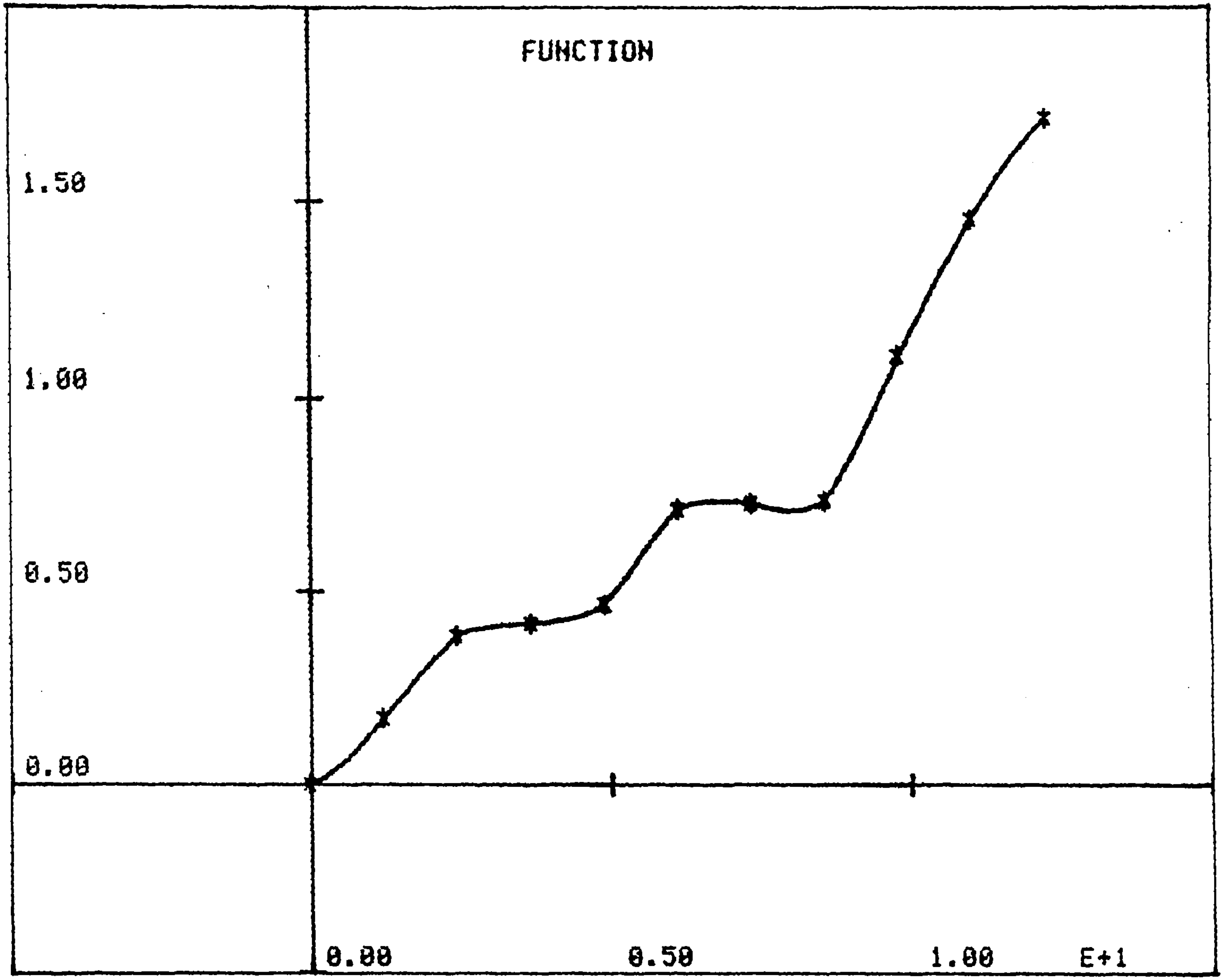


FIGURE 36

VIII. COMPUTATION OF LIGHTNING ELECTRIC FIELDS

In section VII, a rectenna was simulated in the presence of a uniform electric field of 100,000 Volts. The induced surface charges derived from the simulation are directly proportioned to the imposed electric field strength.

In this section we describe a computer program that was written to derive values for the lightning-produced electric fields as a function of time and of distance from "ground zero" - the point of strike. We have run the program for a range of lightning parameters obtained from actual measurements reported in the literature.

The program computes the contribution to the electric field from the thundercloud charge center participating in the cloud-to-ground flash, the charge on the lightning channel, and the images of these charges. All charges are allowed to vary with time in a manner consistent with observations [Terrestial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1977 Revision; Edited by John W. Kaufman, NASA Technical Memorandum 78118].

Figure 37 displays the relevant equations and configurations covering the leader phases of the computation.

In Figure 38 the equations and conditions during the return stroke portion are shown. The program used in computing the fields is provided in the appendix.

The material following Figure 38 provides the tabular and graphic data used in these computations for the return stroke phase. These data are contained in Figures (39-44) inclusive.

The output of the computer program is a "blow-by-blow" history of the electrical field at a specified distance from ground zero as a function of time. Figure 45 displays one section of the output from one of the computer runs. This corresponds to a worst-case situation, 10 meters away from the very-severe-model. The units of time are seconds(along the abscissa), and the units of the ordinate are kilovolts per meter.

Table 8.4 in figure 46 provides a summary of the output for the various computer runs. Listed are the peak negative fields, the peak positive fields (when positive fields occur), and the ΔE and ΔT for the portion of the flash with the peak rate of change of electric field.

These values are our input data to the computation of diode failure when used in conjunction with the induced surface charge results of the rectenna electrostatic simulations.

STEPPED OR DART LEADER PROCESSES:

INITIAL SPECIFICATIONS

TEMPORAL FUNCTIONS:

$$\left\{\begin{array}{l} Y_0 \ (\sim 5 \text{ KM}) \\ Q_0 \ (\sim -10 \text{ Coul}) \\ V_L \ (\sim 10^5 \text{ M/s}) \\ T = 0 \ , \quad Y = Y_0 \\ Q_L \ (\sim -5 \text{ Coul}) \\ P = P_L = Q_L/Y_0 \end{array}\right.$$

$$X = Y_0 - V_L T$$

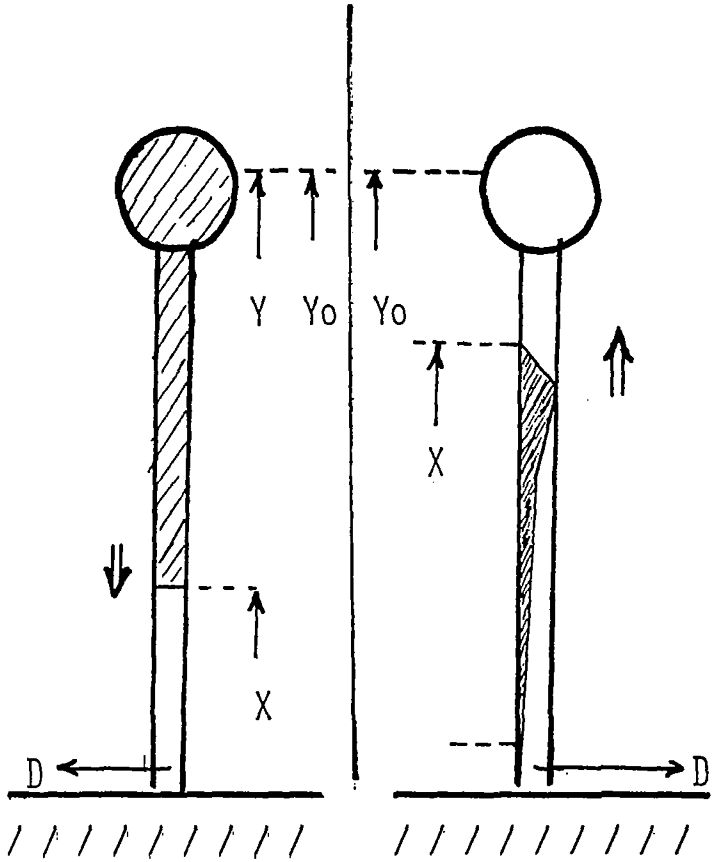
$$Q = Q_0 - P_L (Y - X)$$

SOLVE FOR $E_L(T,D)$ FOR $T \leq T_L$ WHERE

$T_L = (Y_0 - X_L)/ V_L$

X_L ($\sim$50 METERS)

FOR $T > T_L$, $E_L(T,D) = E_L(T_L,D)$



$$E = \frac{2P}{4\pi\varepsilon_0}\left\{\frac{1}{(D^2 + X^2)^{1/2}} - \frac{1}{(D^2 + Y^2)^{1/2}}\right\} + \frac{2\,QY_0}{4\pi\,\varepsilon_0\,(D^2 + Y_0^2)^{3/2}}$$

FIGURE 37

RETURN STROKE PROCESS:

INITIAL SPECIFICATIONS

Y_0, Q_0, Q_L

SAME AS LEADER PROCESS

$T' = T - T_L$

V_R ($\sim 5 \times 10^7$ M/s)

$X = 0$

I(T)  SIGN OPPOSITE TO Q_0

TEMPORAL FUNCTIONS:

$$Y = V_R T'$$

$$\left. \begin{aligned} P &= \int I\,dT / Y \\ Q &= 0 \end{aligned} \right\} \quad \text{FOR } Y < Y_0$$

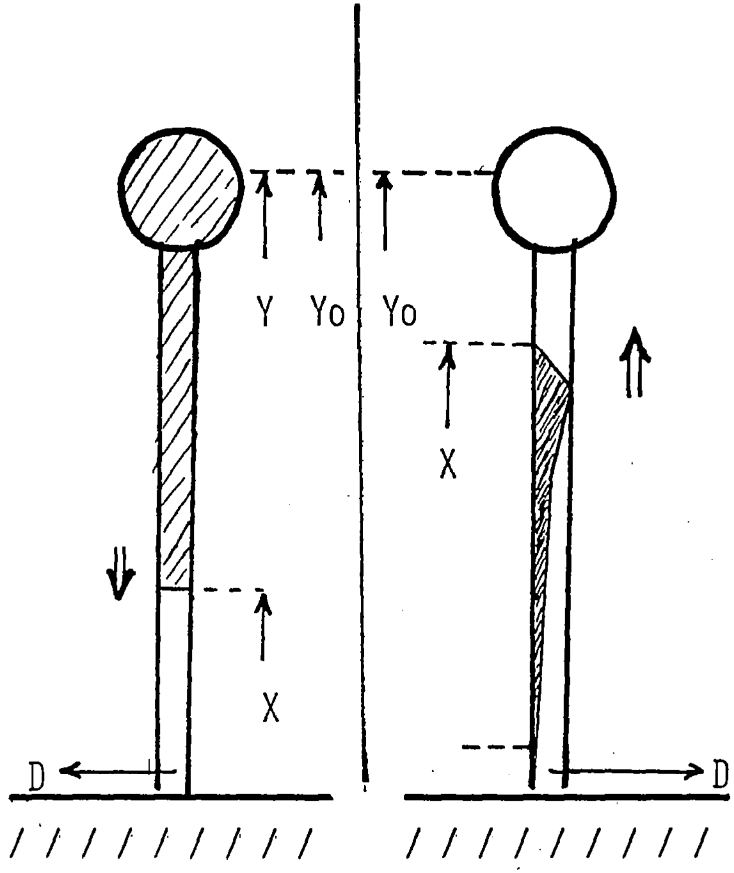
$$\left. \begin{aligned} P &= \int I\,dT / Y_0 \\ Q &= 0 \end{aligned} \right\} \quad \text{FOR } Y > Y_0 \ \underline{\text{AND}} \ P \leq -P_L$$

$$\left. \begin{aligned} P &= -P_L \\ Q &= \int I\,dT + Q_L \end{aligned} \right\} \quad \begin{aligned} &\text{FOR } Y > Y_0 \ \underline{\text{AND}} \ P > -P_L \\ &\underline{\text{AND}} \ Q \leq -(Q_0 - Q_L) \end{aligned}$$

SOLVE FOR $E_R(T', D)$ FOR $T > T_L$ OR $T' > 0$

TOTAL FIELD $E_T(T,D) = E_L(T_L, D) + E_R(T,D)$

TERMINATE COMPUTATION WHEN $Q \geq -(Q_0 - Q_L)$



$$E = \frac{2P}{4\pi\varepsilon_0} \left\{ \frac{1}{(D^2 + X^2)^{1/2}} - \frac{1}{(D^2 + Y^2)^{1/2}} \right\} + \frac{2\,QY_0}{4\pi\varepsilon_0\,(D^2 + Y_0^2)^{3/2}}$$

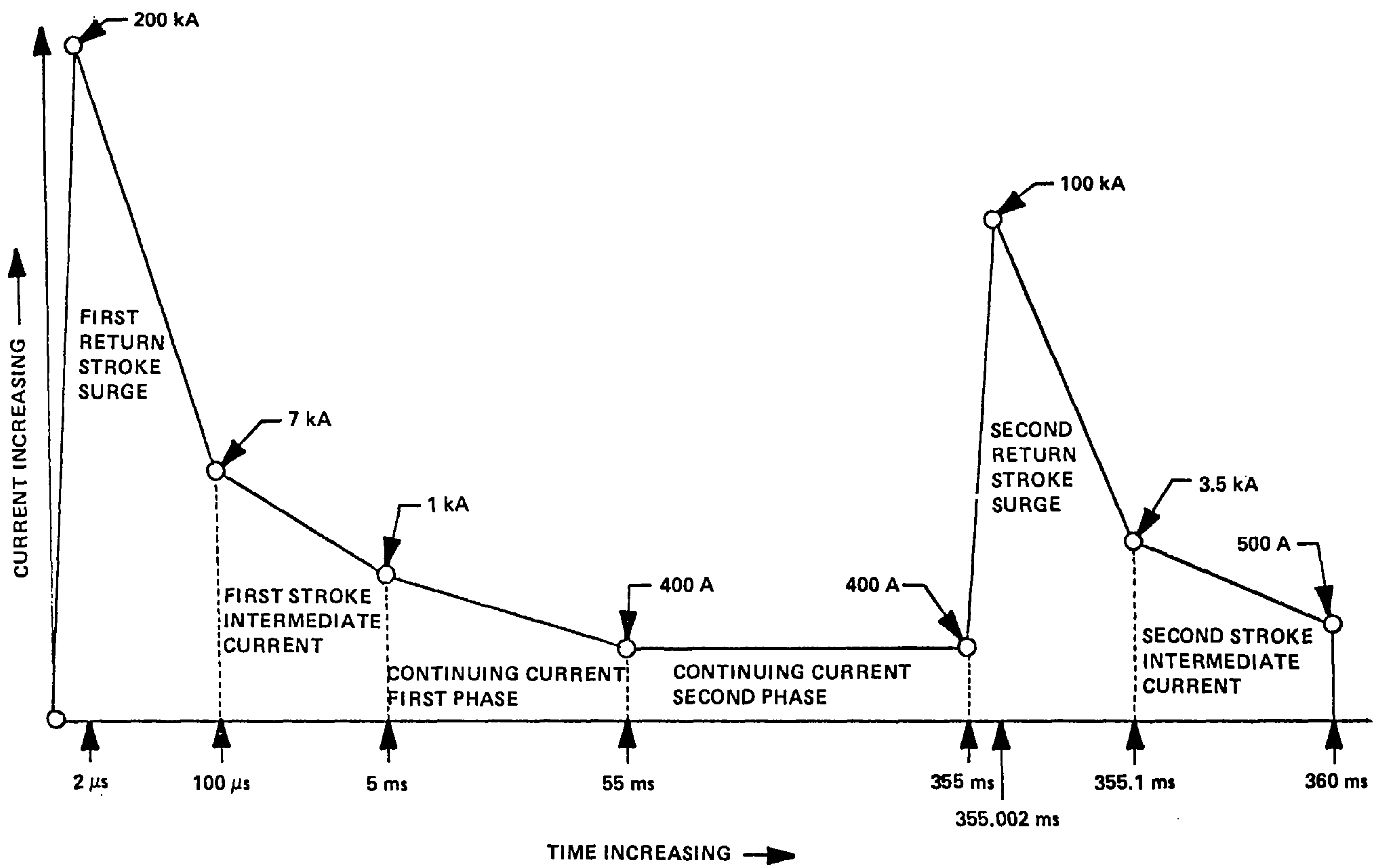
FIGURE 38

DETAILS OF A VERY SEVERE LIGHTNING MODEL (MODEL 1)

Stage	Key Points	Rate of Current Change	Charge Passing
1. First Return Stroke Surge	t = 0 i = 0 t = 2 μs i = 200 kA t = 100 μs i = 7 kA	Linear Rise - 100 kA/μs Linear Fall - 193 kA in 98 μs	0.2 C* ~ 10.2 C
2. First Stroke Intermediate Current	t = 100 μs i = 7 kA t = 5 ms i = 1 kA	Linear Fall - 6 kA in 4.9 ms	19.6 C
3. Continuing Current--First Phase	t = 5 ms i = 1 kA t = 55 ms i = 400 A	Linear Fall - 600 A in 50 ms	35.0 C
4. Continuing Current--Second Phase	t = 55 ms i = 400 A t = 355 ms i = 400 A	Steady Current	120.0 C
5. Second Return Stroke Surge	t = 355 ms i = 400 A t = 355.002 ms i = 100 kA t = 355.1 ms i = 3.5 kA	Linear Rise ~ 50 kA/μs Linear Fall - 96.5 kA in 98 μs	~ 0.1 C ~ 5.1 C
6. Second Stroke Intermediate Current	t = 355.1 ms i = 3.5 kA t = 360 ms i = 500 A	Linear Fall - 3 kA in 4.9 ms	9.8 C

* Coulomb (C) is the quantity of electricity transported in one second by a current of one ampere.

FIGURE 39



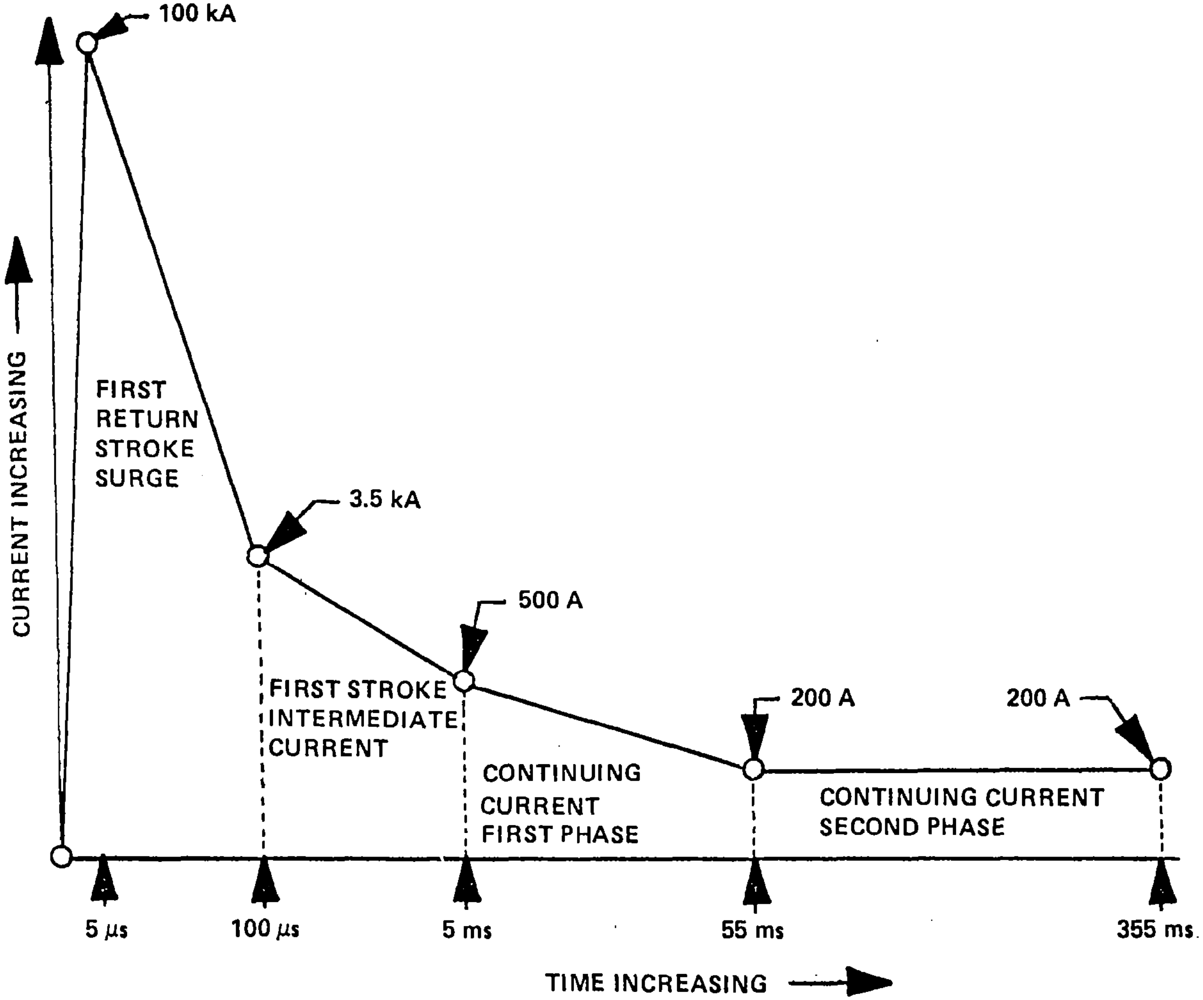
DIAGRAMMATIC REPRESENTATION OF A VERY SEVERE LIGHTNING MODEL (MODEL 1) (Note that the diagram is not to scale)

FIGURE 40

DETAILS OF A 98 PERCENTILE PEAK CURRENT LIGHTNING MODEL (MODEL 2)

Stage	Key Points	Rate of Current Change	Charge Passing
1. First Return Stroke Surge	$t = 0$ $i = 0$ $t = 5\ \mu s$ i 100 kA $t = 100\ \mu s$ i 3.5 kA	Linear Rise - 20 kA/μs Linear Fall - 96.5 kA in 95 μs	0.3 C ~ 4.9 C
2. First Stroke Intermediate Current	$t = 100\ \mu s$ i 3.5 kA $t = 5$ ms i 500 A	Linear Fall - 3 kA in 4.9 ms	9.8 C
3. Continuing Current--First Phase	$t = 5$ ms i 500 A $t = 55$ ms i 200 A	Linear Fall - 300 A in 50 ms	17.5 C
4. Continuing Current--Second Phase	$t = 55$ ms i 200 A $t = 355$ ms i 200 A	Steady Current	60 C

FIGURE 41



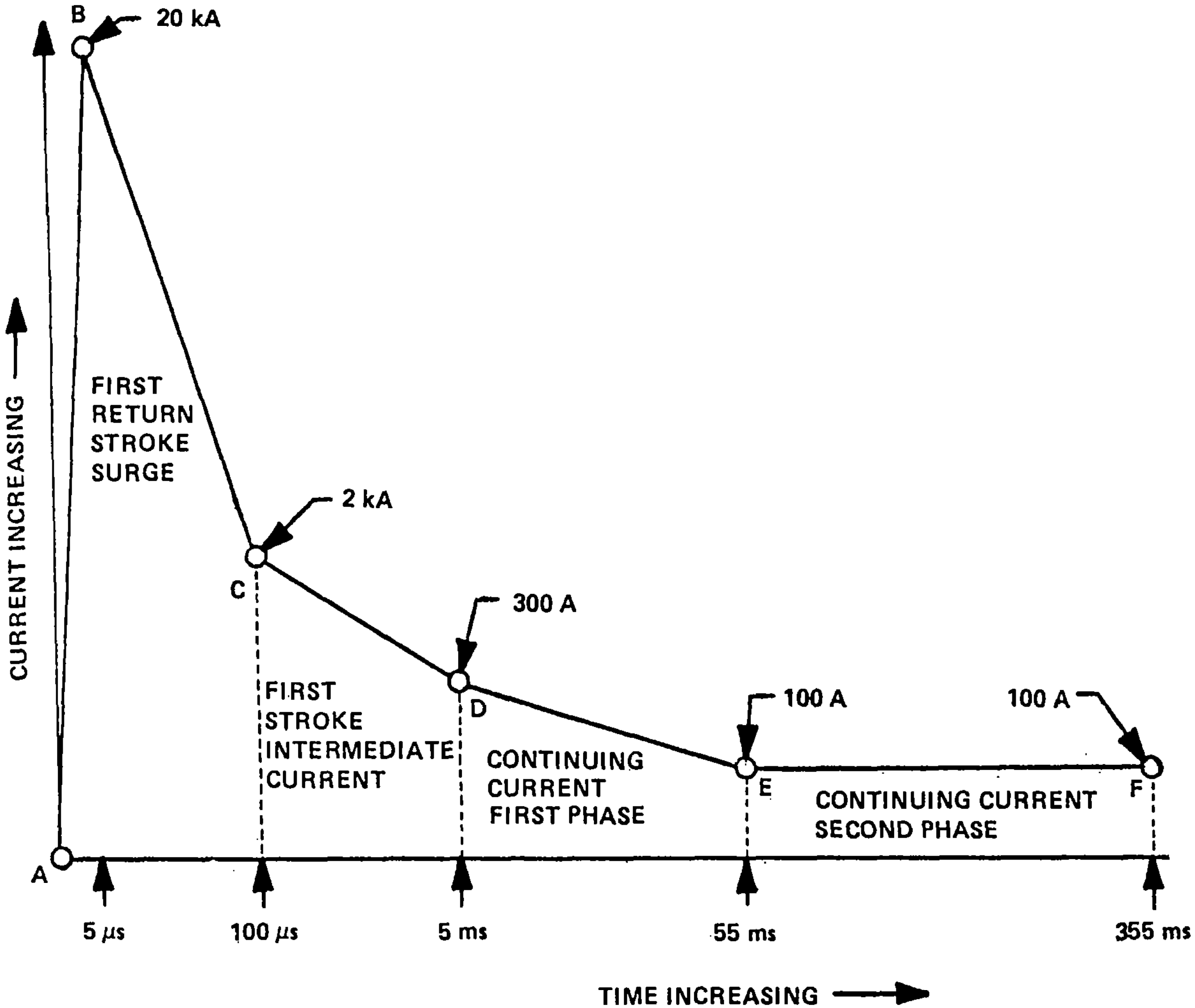
DIAGRAMMATIC REPRESENTATION OF A 98 PERCENTILE PEAK CURRENT LIGHTNING MODEL (MODEL 2) (Note that the diagram is not to scale.)

FIGURE 42

DETAILS OF AN AVERAGE LIGHTNING MODEL (MODEL 3)

Stage	Key Points		Rate of Current Change	Charge Passing
1. First Return Stroke Surge	t = 0 t = 5 μs t = 100 μs	i = 0 i = 20 kA i = 2 kA	Linear Rise - 4 kA/μs Linear Fall - 18 kA in 95 μs	0.1 C ~ 1.0 C
2. First Stroke Intermediate Current	t = 100 μs t = 5 ms	i = 2 kA i = 300 A	Linear Fall - 1.7 kA in 4.9 ms	5.6 C
3. Continuing Current -- First Phase	t = 5 ms t = 55 ms	i = 300 A i = 100 A	Linear Fall - 200 A in 50 ms	10.0 C
4. Continuing Current -- Second Phase	t = 55 ms t = 355 ms	i = 100 A i = 100 A	Steady Current	30.0 C

FIGURE 43



DIAGRAMMATIC REPRESENTATION OF AN AVERAGE LIGHTNING MODEL (MODEL 3) (Note that the diagram is not to scale.)

FIGURE 44

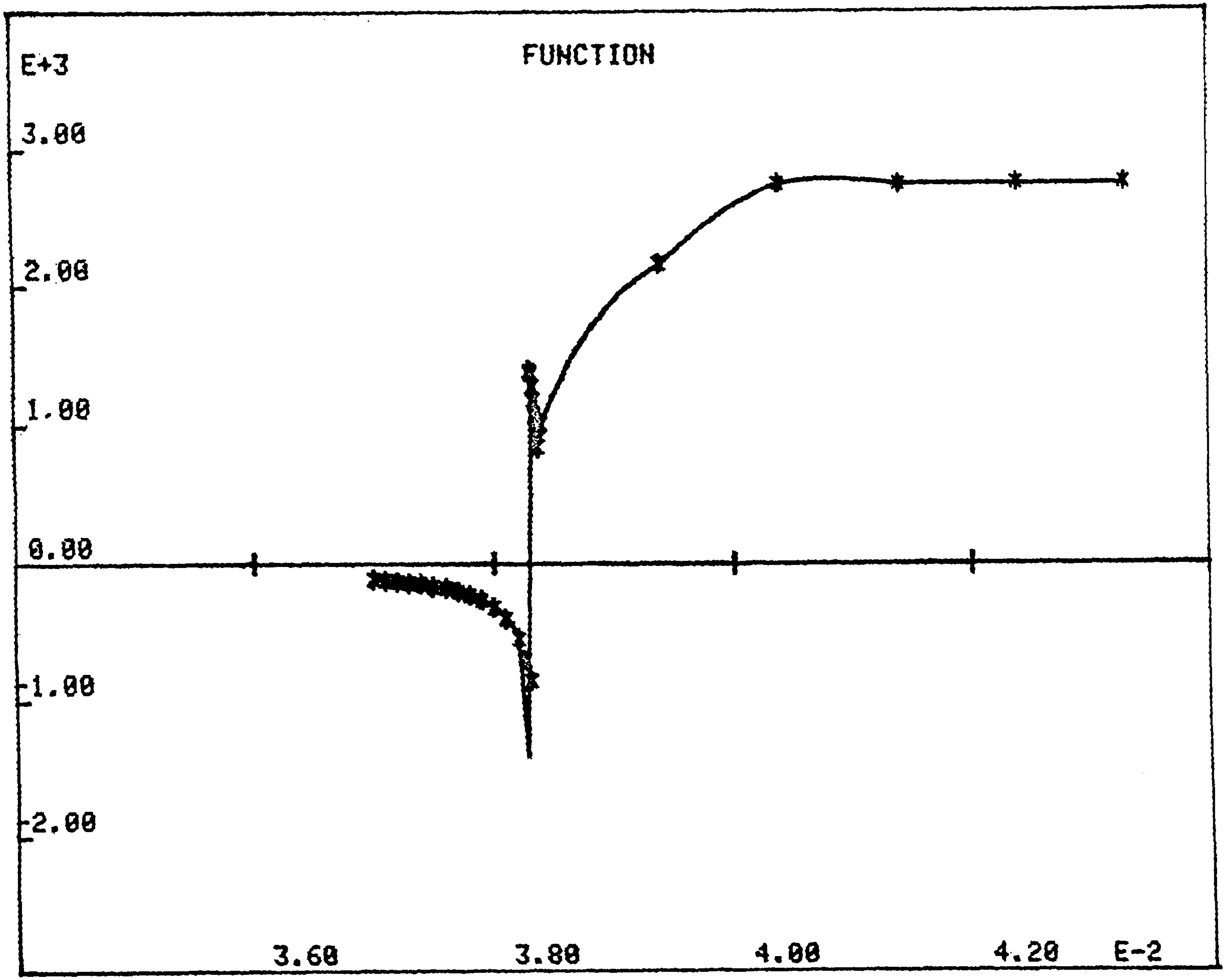


FIGURE 45

TABLE 8.4

Distance	VERY SEVERE MODEL Peak Negative	Peak Positive	ΔE/ΔT Peak	98 PERCENTILE MODEL Peak Negative	Peak Positive	ΔE/ΔT Peak	AVERAGE MODEL Peak Negative	Peak Positive	ΔE/ΔT Peak
10 m	-8.5×10^{5}	2.8×10^{6}	$\frac{2.2\times10^{6}}{1.2\times10^{-5}}$	-5.95×10^{5}	1.81×10^{6}	$\frac{6.46\times10^{5}}{3.00\times10^{-6}}$	-5.09×10^{5}	1.30×10^{6}	$\frac{5.68\times10^{5}}{2.59\times10^{-5}}$
50 m	-5.7×10^{5}	1.7×10^{5}	$\frac{4.37\times10^{5}}{2.2\times10^{-5}}$	-3.88×10^{5}	1.04×10^{5}	$\frac{3.59\times10^{5}}{2.5\times10^{-5}}$	-3.10×10^{5}	6.1×10^{4}	$\frac{1.14\times10^{5}}{2.50\times10^{-5}}$
100 m	-3.49×10^{5}	2.49×10^{4}	$\frac{2.15\times10^{5}}{2.2\times10^{-5}}$	-2.36×10^{5}	N/A	$\frac{1.75\times10^{5}}{2.5\times10^{-5}}$	-1.85×10^{5}	N/A	$\frac{5.47\times10^{4}}{3.5\times10^{-5}}$
500 m	-8.94×10^{4}	N/A	$\frac{3.79\times10^{4}}{3.2\times10^{-5}}$	-6.15×10^{4}	N/A	$\frac{2.96\times10^{4}}{4.5\times10^{-5}}$	-5.12×10^{4}	N/A	N/A
1000 M	-5.35×10^{4}	N/A	$\frac{1.69\times10^{4}}{4.2\times10^{-5}}$	-2.61×10^{4}	N/A	N/A	-3.29×10^{4}	N/A	N/A

FIGURE 46

IX. COMPUTATIONS OF DIODE FAILURE

We are now to the point of having generated all of the data that are required to evaluate the conditions under which the microwave rectifier diodes will fail due to induced currents from nearby lightning flashes. For a given ΔE and ΔT (from Table 8.4) we obtain from Figure 31 the power required for diode failure and from Figure 32 the induced charge/unit area on the rectenna surface. We assume that a diode designed to operate at 67 V will have a breakdown voltage of about 100 Volts.

The surface area of the rectenna that has an induced surface charge of the size sufficient to cause diode failure is then computed from comparison with areas of the rectenna served by individual diodes and by series strings of diodes. Sample computations follow.

SAMPLE COMPUTATION OF DIODE FAILURE (98TH PERCENTILE - 10 METER - NO PROTECTION)

1. 98 percentile model - 10 meters: $\Delta T = 3 \times 10^{-6}$ and $\Delta E = 6.46 \times 10^{5}$.
2. Expected diode failure power from Figure 30: 250 Watts.
3. Energy dissipated in the diode: 250 Watts x 3×1^{-6} s = 7.5×10^{-4} Joules.
4. Charge transferred across 100 Volts diode breakdown voltage = 7.5×10^{-6} Coulombs.
5. From ΔE in step 1 and figure 37, the induced charge/unit area = 3×10^{-6} c/m^2 x 6.46 = 19.38×10^{-6} c/m^2.
6. From steps 4 and 5, the rectenna area with surface charge equivalent to the charge required to cause diode failure is: 0.39 m^2.
7. Area served by diodes: rectenna center, .

   $$\frac{25 \text{ watts}}{230 \text{ w/m}^2} = 0.11 \text{ m}^2; \text{ rectenna edge}, \frac{25 \text{ watts}}{10 \text{ w/m}^2} = 2.5 \text{ m}^2.$$
8. Compare 6 with 7: single diode configuration near rectenna center is safe. Single diode configuration near rectenna edge is vulnerable.
9. <u>However</u>, the diodes are to be put in series (597 to a string) hence the diodes near the bottom must carry all of the induced current to the entire string. For these bottom-string diodes the area served with respect to the induced charge is: rectenna center, 60 m^2; rectenna edge, 1400 m^2.
10. To protect against the 98 percentile flash within 10 meters of ground zero would require fast surge protection diodes (back to back zeners) on all diodes in the rectenna. This extent of protection may not be cost effective; however the considerations in Section X indicate that simpler protection arrangements will probably be effective near the rectenna center.

FAILURES PRODUCED BY THE AVERAGE LIGHTNING FLASH

The situation considered here is the extent of the protection required for an "average" lightning flash if we are willing to accept losses from the extreme cases.

The computation sequence follows the same procedure described immediately above. Here we use data for the average flash from Table 8.4 at a 10 m distance from ground zero.

SAMPLE COMPUTATION OF DIODE FAILURE
(AVERAGE FLASH, 10 M, WITH "STATIC" PROTECTION)

1. From Table 8.4: $\Delta E = 5.68 \times 10^{5}$ v/m; $\Delta T = 2.59 \times 10^{-5}$ s.
2. From Figure 6.1: 80 watts.
3. 80 w x 2.59×10^{-5} s $\simeq 2 \times 10^{-3}$ Joules.
4. 2×10^{-5} coulombs.
5. From 1 and Figure 38: $1.5 \times 10^{-6} \times 5.68 = 8.52 \times 10^{-6}$ coul/m^2.
6. From 4 and 5: Area = 2.35 m^2.
7. Since the rectenna area served by individual diodes even on the edge < 2.5 m^2, the individual diodes are self-protecting and able to take an "average" lightning flash.
8. However, when arranged in a series stack of 597, the diodes at the bottom of the stack must conduct the induced currents for the whole stack. The diodes cannot safely carry these currents.

X. LIGHTNING PROTECTION FOR SERIES DIODE STRINGS

As demonstrated in Section IX, the connection of microwave rectifier diodes in series requires special lightning protection considerations. We cannot make specific recommendations for these protection devices at this time because the rectenna current design is not advanced to the point that allows such detailed analysis. Rockwell International has provided us with an equivalent circuit for the rectenna; a slightly modified form of that circuit is shown in Figure 46. We have assumed that the series connections are to be made at the points indicated by the large spots and that the output filler operates around 30 Hz. A series string of rectenna elements of this design can be protected with a variety of methods. One cost-effective means is a spark gap arrangement incorporated in the diode feedthroughs, or the output filter inductors, or on the billboard configuration itself.

RECTENNA EQUIVALENT CIRCUIT AT 2.45 GHz

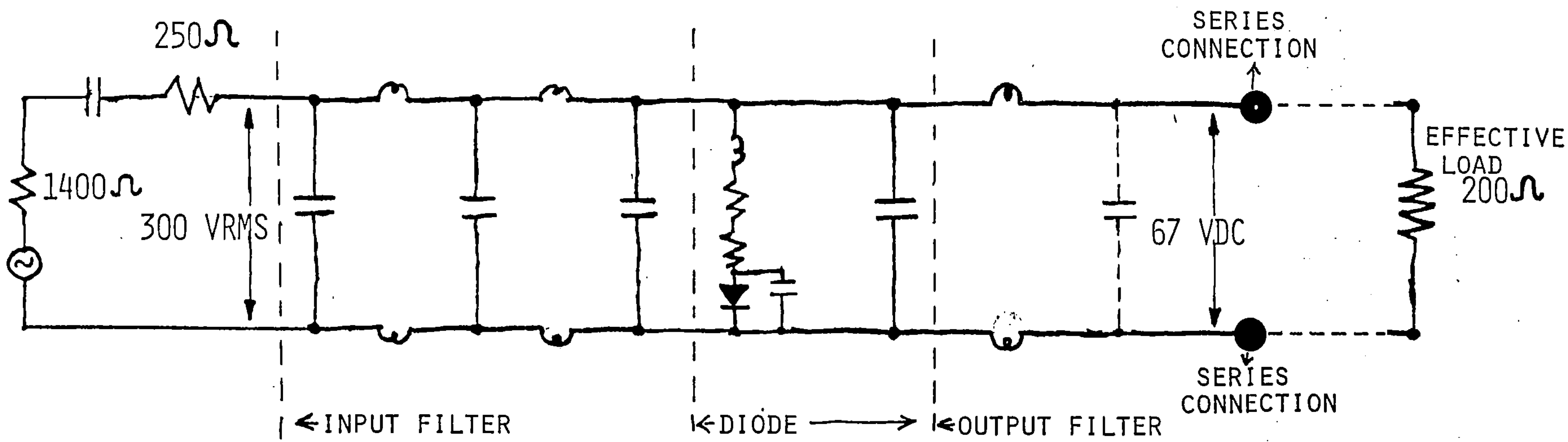


FIGURE 46

XI. CLOUD-TO-GROUND LIGHTNING DISTRIBUTION IN THE UNITED STATES

In order to have a working estimate of the hazard presented by lightning to rectennas, we need to know the cloud-to-ground lightning flash density for various possible rectenna sites in the United States. The cloud-to-ground lightning flash density (in $\#/km^2$ for example) is not a parameter that is measured as a climatological variable. We have found it necessary to use the number-of-thunderstorm days as a proxy variable because it is available as a climatological variable. Figure 47 gives contours of annual number-of-thunderstorm days.

XI.1. Pierce Conversion Formula

Several attempts have been made to derive a conversion formula to convert thunderstorm days into the flash density by using lightning flash counters in research areas for correlation with the count of thunderstorm days. The best of the various conversion formulas is that due to E.T. Pierce ("A Relationship Between Thunderstorm Days and Lightning Flash Density," Trans. AGU, 49, 686, 1967.) The Pierce formula (as does most others) has a quadratic term, which reflects the relationship between frequencies of local storms and storm intensity. In addition, the formula utilizes the monthly thunderstorm days as opposed to the annual average in order to incorporate seasonal effects in the conversion formula.

This formula is

$$\sigma_M^2 = aT_M + a^2T_M^4,$$

where: T_M = monthly number of thunderstorm days and σ_M is the monthly ground flash density ($\#km^2$/Mt.) The parameter a is,

$$a = 3 \times 10^{-2}$$

If σ is the annual ground flash density ($\#\ km^{-2}$/yr.), then

$$\sigma = \sum_{M=1}^{12} \sigma_M.$$

XI.2. Climatological Data -- Number of Thunderstorm Days

The inputs needed to compute the U.S. Distribution of ground lightning flash density are: (1) The monthly number of thunderstorm days for all U.S. stations recording these observations, (2) the coordinates of the observing sites, and (3) the computer software to compute the density and display the results geographically.

Items 1 and 2 were obtained from "Local Climatological Data - Annual Summaries for 1977" published by The National Oceanic and Atmospheric Administration on magnetic tape. The geographic plotting software of Item 3 was obtained from The National Technical Information Service, and the computer programming was done by J.L. Bohannon at Rice.

A detailed list of flash density for all of the stations used is provided in the Appendix.

Note the hot spots on the contours in Figure 48 that result when stations are located near geographic features that promote local thunderstorms. There are probably other similar hot spots in the U.S. that do not show up on this display because of the absence of an observing station nearby.

UNITED STATES DISTRIBUTION OF THE NUMBER OF THUNDERSTORM DAYS

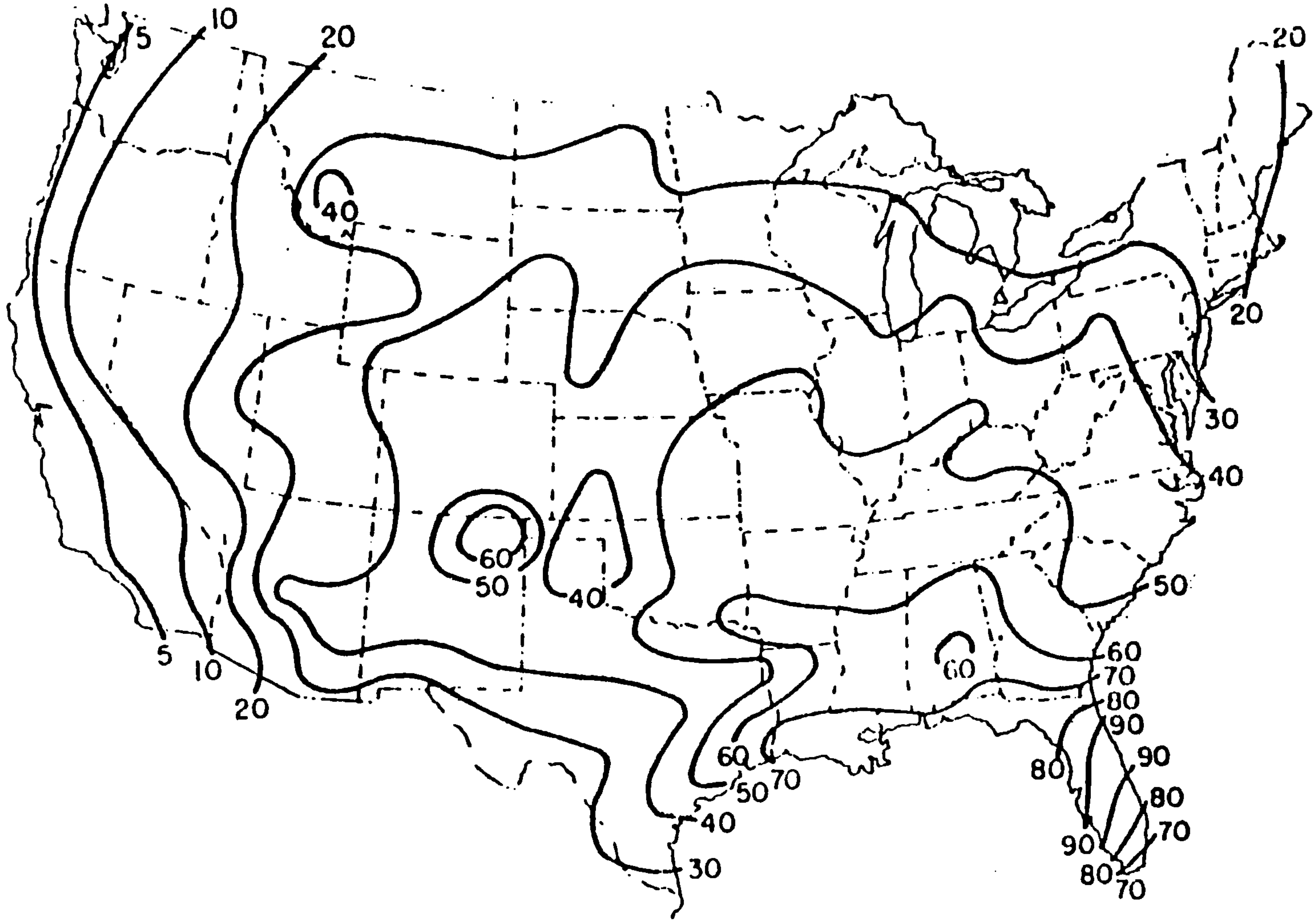


FIGURE 47

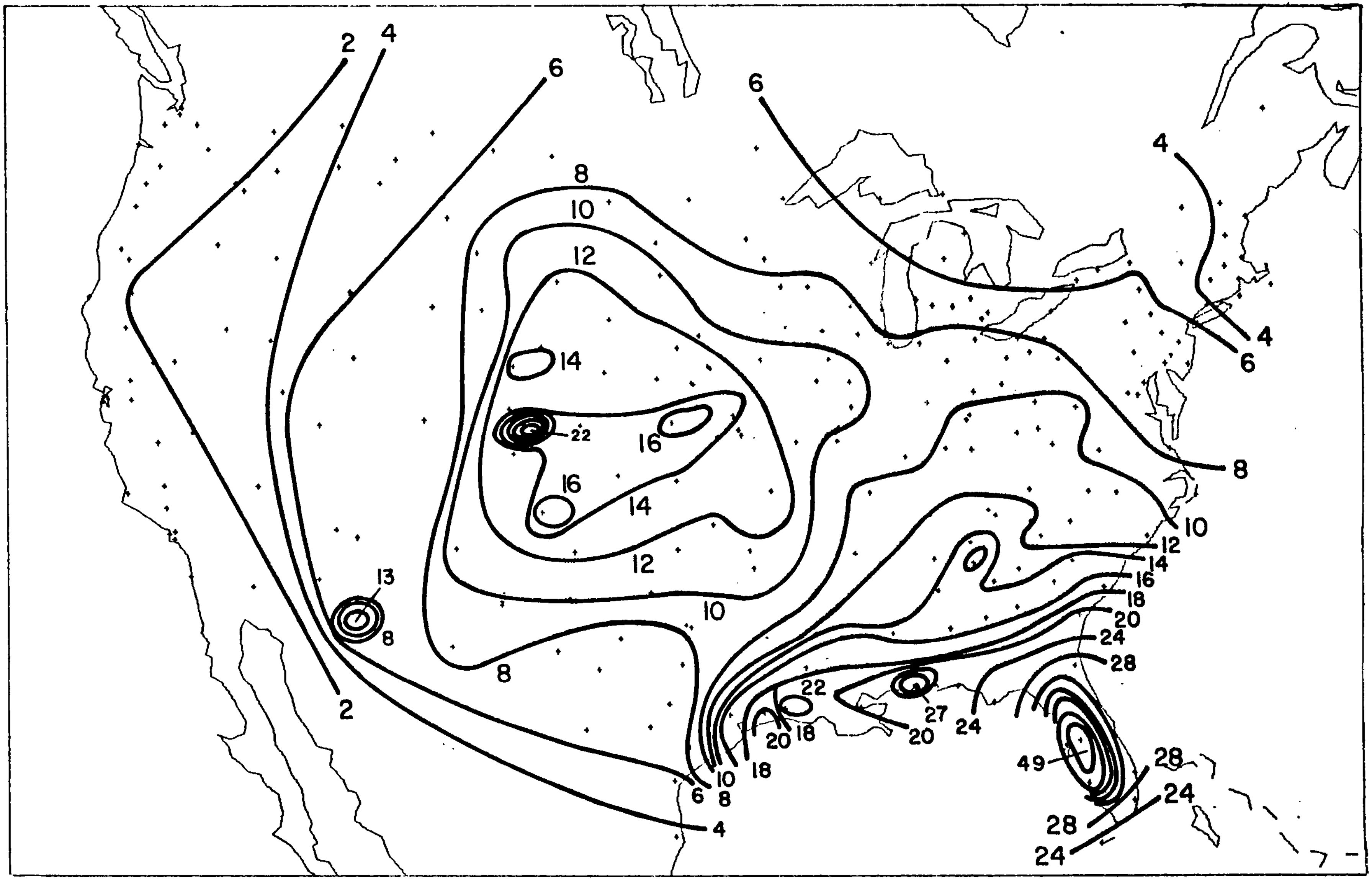

2
4
6
6
4
8
10
12
14
22
16
16
14
12
10
8
13
8
2
4
6
8
10
8
10
12
14
16
18
20
24
28
22
27
18
20
20
24
49
28
24
28
24

FIGURE 48

APPENDICES

Computer programs developed under this contract.

All programs are in FORTRAN H, unless otherwise specified. All of the programs were run on an IBM 370/155 and/or an Itel AS/6 computer.

Apendix A

Computer Program PANEL:
A Computer Model of the SPS Plasma Interaction

The following pages are the listing of the program "PANEL," written to model the interaction of a high voltage solar array with an ambient Maxwellian plasma. The program was originally written by Dr. Lee W. Parker and was modified for application to the SPS problem by David L. Cooke.

A2

PANEL

7 24(

COOKE

```
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
PRINTER3 A   END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
 INTER3 A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
  NTER3 A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
    ER3 A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
      3 A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
        A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
             END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
  NTR        END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
  NTE        END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
  NTE        END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
  NTER3 A    END JOB 2404  BIN 7   COOKE  437075SCPS  4:02:00 PM 27 MAR 79  PANEL
```

```
                 COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                                    SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                        C
                        C          SOLAR PANEL PROBLEM
      ISN 0002                     COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,
                                  1 TVOLTS,CUR,XMETER
      ISN 0003                     COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                                  1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                                  2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
      ISN 0004                     COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
      ISN 0005                     COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
      ISN 0006                     COMMON/INTER/INT,IIA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,
                                  1XI(30),YJ(20),ZK(10)
      ISN 0007                     DIMENSION DATE(20)
      ISN 0008                     DIMENSION VFC(4),IF(4),JF(4),KF(4)
      ISN 0009                     INTEGER SKPRFL,SKPLST,SKPCO
      ISN 0010                     NF(IX,JX,KX)=IX+II*(JX-1)+II*JJ*(KX-1)
      ISN 0011                     L=5
      ISN 0012                     M=6
      ISN 0013           100       READ(L,9999,END=99) DATE
      ISN 0014          9999       FORMAT(20A4)
      ISN 0015             2       WRITE(M,9998) DATE
      ISN 0016          9998       FORMAT(42H1SOLAR PANEL ELECTRIC FIELD AND CURRENTS. ,20A4)
                        C          READ GEOMETRIC PARAMETERS
                        C
      ISN 0017                     READ(L,111) IIP,IIM,JJP,JJM,KK,IV,JV
      ISN 0018                     II=IIM+IIP-1
      ISN 0019                     JJ=JJM+JJP-1
      ISN 0020                     NTOT=II*JJ*KK
      ISN 0021                     READ(L,222) (XP(I),I=1,IIP)
      ISN 0022                     READ(L,222) (XM(I),I=1,IIM)
      ISN 0023                     READ(L,222) (YP(J),J=1,JJP)
      ISN 0024                     READ(L,222) (YM(J),J=1,JJM)
      ISN 0025                     READ(L,222) (ZZ(K),K=1,KK)
                        C          READ PANEL POTENTIALS
      ISN 0026                     READ(L,116)(VP(I),I=1,IV),VRF
      ISN 0027                     READ(L,111)SKPRFL,SKPLST,ILX,IUX,KLK,KUK,MBC,MBD,NFPS,SKPCO
      ISN 0028                     DO 140 NPC=1,NTOT
      ISN 0029                     X(NPC,1)=0
      ISN 0030           140       X(NPC,2)=0
      ISN 0031                     IIM1= IIM+IV-1
      ISN 0032                     JJM1 = JJM+JV-1
      ISN 0033                     DO 150 I = IIM,IIM1
      ISN 0034                     DO 150  J = JJM,JJM1
      ISN 0035                     III = I+1-IIM
      ISN 0036                     N = NF(I,J,1)
      ISN 0037                     X(N,1) = VP(III)
      ISN 0038                     X(N,2) = 1
      ISN 0039           150       CONTINUE
                        C
                        C          CONSTRUCT REFLECTORS
      ISN 0040                     IF(SKPRFL.EQ.1)GO TO 163
      ISN 0042                     DO 160 I = ILX,IUX
      ISN 0043                     DO 160 K = KLK,KUK
      ISN 0044                     JW = MBC-K
      ISN 0045                     NW = NF(I,JW,K)
      ISN 0046                     X(NW,1) = VRF
      ISN 0047                     X(NW,2) = 1
```

```
ISN 0048          JW = K+MBD
ISN 0049          NW = NF(I,JW,K)
ISN 0050          X(NW,2) = 1
ISN 0051          X(NW,1) = VRF
ISN 0052    160   CONTINUE
ISN 0053          WRITE(M,231) VRF
ISN 0054    231   FORMAT(//1X,'REFLECTOR POTENTIAL = ',1PE15.5)
            C
            C     READ ADDITIONAL FIXED POTENTIALS
ISN 0055    163   IF(NFPS.LE.3)GO TO 220
ISN 0057          WRITE(M,118)
ISN 0058    118   FORMAT(//'ADDITIONAL FIXED POTENTIALS'/
                 14(6X,'POT',7X,'I',3X,'J',3X,'K' ))
ISN 0059          DO 170 NQC = 1,NFPS,4
ISN 0060          READ(L,119)(VFC(I),IF(I),JF(I),KF(I),I=1,4)
ISN 0061    119   FORMAT(4(E8.0,3I4))
ISN 0062          WRITE(M,117)(VFC(I),IF(I),JF(I),KF(I), I=1,4 )
ISN 0063    117   FORMAT(/4(3X,1PE10.2,3I4))
ISN 0064    165   DO 170 I=1,4
ISN 0065          NN = NF(IF(I),JF(I),KF(I))
ISN 0066          X(NN,1)=VFC(I)
ISN 0067          X(NN,2)=1
ISN 0068    170   CONTINUE
ISN 0069    220   CONTINUE
ISN 0070          IVP=IV+1
ISN 0071          JVP=JV+1
ISN 0072          WRITE(M,113)IIP,IIM,JJP,JJM,KK,IV,JV
ISN 0073          WRITE(M,223) (I,XP(I),I=1,IV)
ISN 0074          WRITE(M,224) (I,XP(I),I=IVP,IIP)
ISN 0075          WRITE(M,225) (I,XM(I),I=1,IIM)
ISN 0076          WRITE(M,226) (J,YP(J),J=1,JV)
ISN 0077          WRITE(M,227) (J,YP(J),J=JVP,JJP)
ISN 0078          WRITE(M,228) (J,YM(J),J=1,JJM)
ISN 0079          WRITE(M,229) (K,ZZ(K),K=1,KK)
ISN 0080          WRITE(M,230) (XP(I),I=1,IV)
ISN 0081          WRITE(M,241)(VP(I),I=1,IV)
            C
ISN 0082    111   FORMAT(16I5)
ISN 0083    113   FORMAT(//1X,I3,18H POSITIVE X-VALUES/
                 1              1X,I3,18H NEGATIVE X-VALUES/
                 2              1X,I3,18H POSITIVE Y-VALUES/
                 3              1X,I3,18H NEGATIVE Y-VALUES/
                 4              1X,I3,25H Z-VALUES (POSITIVE ONLY)/
                 5              1X,I3,33H POSITIVE X-VALUES DEFINING PANEL/
                 6              1X, I3,33H POSITIVE Y-VALUES DEFINING PANEL)
ISN 0084    116   FORMAT(8E10.0)
ISN 0085    222   FORMAT(16F5.0)
ISN 0086    223   FORMAT(//1X,27HX-VALUES POSITIVE ON PANEL=/(I3,1PE15.4))
ISN 0087    224   FORMAT(//1X,35HX-VALUES POSITIVE OUTSIDE OF PANEL=/(I3,1PE15.4))
ISN 0088    225   FORMAT(//1X,18HX-VALUES NEGATIVE=/(I3,1PE15.4))
ISN 0089    226   FORMAT(//1X,27HY-VALUES POSITIVE ON PANEL=/(I3,1PE15.4))
ISN 0090    227   FORMAT(//1X,35HY-VALUES POSITIVE OUTSIDE OF PANEL=/(I3,1PE15.4))
ISN 0091    228   FORMAT(//1X,18HY-VALUES NEGATIVE=/(I3,1PE15.4))
ISN 0092    229   FORMAT(//1X,37HZ-VALUES (POSITIVE ONLY) ABOVE PANEL=/(I3,1PE15.4))
ISN 0093    230   FORMAT(////1X,25HARRAY OF PANEL POTENTIALS//
                 1 15X,3HX =,3X,(8(F8.4,4X)/20X))
ISN 0094    240   FORMAT(/1X,2HY(,I2,2H)=,F8.4,6X,(8(1PE12.4)/20X))
ISN 0095    241   FORMAT(3X,'ALL Y,',5X,(8(1PE12.4)/20X))
```

```
I.,15I5)
/1X,34HNPRINT,NPTS,MA,MB,ME,KMAX,PROBNO =,6I6,I10/
NUMBER =, F9.1, 9X,13HTEMPERATURE =, F9.1, 6H VOLTS,9X,
     F9.1, 7H PER CC, 9X, 6HMASS =, F9.0,11H ELECTRONS /
TI SCALE =,F9.1,30H METERS = X-DIMENSION OF PANEL)
23HSINGLE SPACE POINT. X =,F10.5,5X, 3HY =,F10.5)
34HSINGLE ENERGY (MONOENERGETIC). E =,F10.5, 6H VOLTS)
27HSINGLE TRAJECTORY. X =,F10.5,5X, 3HY =,F10.5/
LE ALPHA =,F20.8 , 8H DEGREES/
LE BETA  =,F20.8 , 8H DEGREES/
RGY      =,F20.5,  6H VOLTS)
32HRANDOM THERMAL CURRENT DENSITY =,1PE13.4,
FI SQUARE METER, FOR,2A5)
18 INTERFACE X-VALUES/(I3,1PE15.4))
18HINTERFACE Y-VALUES/(I3,1PE15.4))
18HINTERFACE Z-VALUES/(I3,1PE15.4))
 22H -- CURRENTS AND POWER))

II

 GO TO 420

  I

      6
  0 TO 480
  J

 I-1)+XX(I))

 J-1)+YY(J))
```

YY(1) = YM(6) = -5

so YY(11) = 5

YY(6) = 0

A5

```
ISN 0141          ZK(1)=ZZ(1)
ISN 0142          ZK(KKA)=ZZ(KK)
ISN 0143          DO 560 K=2,KK
ISN 0144    560   ZK(K)=.5*(ZZ(K-1)+ZZ(K))
ISN 0145          WRITE(M,561) (I,XI(I),I=1,IIA)
ISN 0146          WRITE(M,562) (J,YJ(J),J=1,JJA)
ISN 0147          WRITE(M,563) (K,ZK(K),K=1,KKA)
            C
ISN 0148          DO 600 N=1,NTOT
ISN 0149          CALL FIND(IFIND,JFIND,KFIND)
ISN 0150          XYZ(N,1)=XX(IFIND)
ISN 0151          XYZ(N,2)=YY(JFIND)
ISN 0152          XYZ(N,3)=ZZ(KFIND)
ISN 0153    600   CONTINUE
            C
ISN 0154          IF(SKPLST.EQ.1) GO TO 660
ISN 0156          NFPP=(NTOT/300)+1
ISN 0157          DO 650 IP=1,NFPP
ISN 0158          WRITE(M,9000)
ISN 0159    9000  FORMAT(1H1/6X,1HN,3X,4HX(N),2X,4HY(N),2X,4HZ(N)//)
ISN 0160          CALL LIST(2,IP)
ISN 0161    650   CONTINUE
ISN 0162    660   CONTINUE
            C
ISN 0163          DO 700 J=1,JJ
ISN 0164          DO 700 I=1,II
ISN 0165          N = NF(I,J,1)
ISN 0166          VV(I,J,1) = X(N,1)
ISN 0167    700   CONTINUE
            C
ISN 0168          K=1
ISN 0169          WRITE(M,8000) K,ZZ(K),(XX(I),I=1,II)
ISN 0170          DO 750 J=1,JJ
ISN 0171          WRITE(M,240)  J,YY(J),(VV(I,J,K),I=1,II)
ISN 0172    750   CONTINUE
            C
ISN 0173          CALL FIELD
            C
ISN 0174          DO 800 K=1,KK
ISN 0175          DO 800 J=1,JJ
ISN 0176          DO 800 I=1,II
ISN 0177          N=NF(I,J,K)
ISN 0178          VV(I,J,K) = X(N,1)
ISN 0179    800   CONTINUE
            C
ISN 0180          DO 900 K=1,KK
ISN 0181          WRITE(M,8000) K,ZZ(K),(XX(I),I=1,II)
ISN 0182    8000  FORMAT(   26H1ARRAY OF POTENTIALS AT Z(,I2,2H)=,F8.4//
                 1 15X,3HX =,3X,(8(F8.4,4X)/20X))
ISN 0183          DO 850 J=1,JJ
ISN 0184          WRITE(M,240)  J,YY(J),(VV(I,J,K),I=1,II)
ISN 0185    850   CONTINUE
ISN 0186    900   CONTINUE
            C
ISN 0187          NPROB=0
ISN 0188     1000 READ(L,333,END=99) NPRINT,NPTS,MA,MB,ME,KMAX,MORE
ISN 0189    1001  READ(L,116) SMACH,TVOLTS,DENCC,XMASS,XMETER
ISN 0190          NPROB=NPROB+1
```

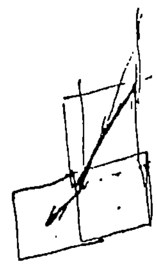
```
ISN 0191            WRITE(M,999)
ISN 0192            WRITE(M,444) NPRINT,NPTS,MA,MB,ME,KMAX,NPROB ,SMACH,TVOLTS,DENCC,
                   1 XMASS,XMETER
ISN 0193            IF(NPTS.EQ.0.OR.ME.EQ.0.OR.MA.EQ.0) READ(L,222)XPT,YPT,AL1,BE1,EV
ISN 0195            IF(NPTS.EQ.0) WRITE(M,445) XPT,YPT
ISN 0197            IF(ME.EQ.0)   WRITE(M,446) EV
ISN 0199            IF(MA.EQ.0)   WRITE(M,447) XPT,YPT,AL1,BE1,EV
ISN 0201            IF(MA.GT.0.AND.XMASS.LE.0.) STOP
ISN 0203            IF(MA.GT.0) CUR=2.68E-8*DENCC*SQRT(ABS(TVOLTS)/XMASS)
ISN 0205            IF(TVOLTS.GT.0.) PARTCL(1)=PART1(1)
ISN 0207            IF(TVOLTS.GT.0.) PARTCL(2)=PART1(2)
ISN 0209            IF(TVOLTS.LT.0.) PARTCL(1)=PART2(1)
ISN 0211            IF(TVOLTS.LT.0.) PARTCL(2 )=PART2(2)
ISN 0213            WRITE(M,448) CUR,PARTCL
ISN 0214            CALL POWER
ISN 0215            IF (MORE.GT.0) GO TO 1000
ISN 0217            GO TO 100
ISN 0218       99   STOP
ISN 0219            END
```

```
              COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                         SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
  ISN 0002                SUBROUTINE ORBIT
                   C
                   C      STEP ACROSS 3-D BOX ASSUMING CONSTANT POTENTIAL WITHIN BOX
                   C
  ISN 0003                COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                         1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                         2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
  ISN 0004                COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE
  ISN 0005                DIMENSION TIME(6),U(3),UDOT(3),B(2,3)
                   C
  ISN 0006                TOOM=3.3333E+33
  ISN 0007                ROUND = 1.E-11
  ISN 0008                TROUND = 1.E-6      (5 x10^-5)
                   C
  ISN 0009                IF(XDOT.EQ.0..AND.YDOT.EQ.0..AND.ZDOT.EQ.0.) WRITE(M,999)
  ISN 0011                IF(XDOT.EQ.0..AND.YDOT.EQ.0..AND.ZDOT.EQ.0.) RETURN
  ISN 0013         999    FORMAT(1X,38HSPEED=0 - HENCE PARTICLE DOES NOT MOVE)
                   C
                   C
  ISN 0014                U(1)=X
  ISN 0015                U(2)=Y
  ISN 0016                U(3)=Z
                   C
  ISN 0017                UDOT(1)=XDOT
  ISN 0018                UDOT(2)=YDOT
  ISN 0019                UDOT(3)=ZDOT
                   C                         NR
  ISN 0020                B(1,1)=X1          1
  ISN 0021                B(2,1)=X2          2
  ISN 0022                B(1,2)=Y1          3
  ISN 0023                B(2,2)=Y2          4
  ISN 0024                B(1,3)=Z1          5
  ISN 0025                B(2,3)=Z2          6
                   C
  ISN 0026                DO 101 N2=1,3
  ISN 0027                IF(UDOT(N2).EQ.0.) GO TO 101
  ISN 0029                DO 100 N1=1,2
  ISN 0030                NR=N1 + 2*(N2-1)
  ISN 0031                TIME(NR)=TOOM
  ISN 0032                TT=(B(N1,N2) - U(N2))/UDOT(N2)
  ISN 0033                SS=U(N2) + UDOT(N2)*TT
  ISN 0034                IF(SS.GE.B(1,N2).AND.SS.LE.B(2,N2)) TIME(NR)=TT
  ISN 0036         100    CONTINUE
  ISN 0037           101  CONTINUE
                   C
                   C    FIND SHORTEST SIGNIFICANT TIME
                   C
  ISN 0038                TIMIN=TOOM
  ISN 0039                DO 200 NR=1,6
  ISN 0040                IF(TIME(NR).EQ.TOOM) GO TO 200
  ISN 0042                IF(TIME(NR).GT.ROUND.AND.TIME(NR).LT.TIMIN) NTIME=NR
  ISN 0044                IF(TIME(NR).GT.ROUND.AND.TIME(NR).LT.TIMIN) TIMIN=TIME(NR)
  ISN 0046         200    CONTINUE
                   C
                   C    ADVANCE TO APPROPRIATE END-POINT
                   C
```

X2 > X1
etc.
>

what on smallest s
if you use the shortest
you'll take the next

SS = U(N2) +

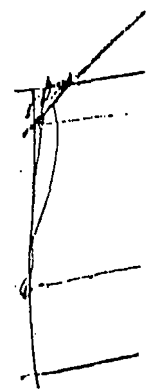


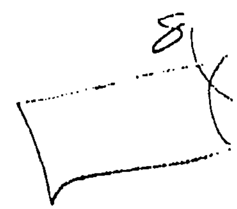
SS = B

A8

X = X + XDOT * (X1

```
ISN 0047          X=X + XDOT*TIMIN
ISN 0048          Y=Y + YDOT*TIMIN
ISN 0049          Z=Z + ZDOT*TIMIN
            C
ISN 0050          XSAV=X
ISN 0051          YSAV=Y
ISN 0052          ZSAV=Z
            C
ISN 0053          IF(NTIME.EQ.1) X=X1
ISN 0055          IF(NTIME.EQ.2) X=X2
ISN 0057          IF(NTIME.EQ.3) Y=Y1
ISN 0059          IF(NTIME.EQ.4) Y=Y2
ISN 0061          IF(NTIME.EQ.5) Z=Z1
ISN 0063          IF(NTIME.EQ.6) Z=Z2
            C
ISN 0065          DX=X-XSAV
ISN 0066          DY=Y-YSAV
ISN 0067          DZ=Z-ZSAV
            C
ISN 0068          IF((NTIME.EQ.1.OR.NTIME.EQ.2).AND.ABS(DX).GT.TROUND) NTIME=-1
ISN 0070          IF((NTIME.EQ.3.OR.NTIME.EQ.4).AND.ABS(DY).GT.TROUND) NTIME=-2
ISN 0072          IF((NTIME.EQ.5.OR.NTIME.EQ.6).AND.ABS(DZ).GT.TROUND) NTIME=-3
ISN 0074          IF(NTIME.EQ.-1) SAVE=XSAV
ISN 0076          IF(NTIME.EQ.-2) SAVE=YSAV
ISN 0078          IF(NTIME.EQ.-3) SAVE=ZSAV
            C
ISN 0080          RETURN
ISN 0081          END
```





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        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
  ISN 0002              SUBROUTINE DEN
                  C
                  C ROUTINE FOR EVALUATING CURRENT-DENSITY INTEGRALS OVER VELOCITY SPACE
                  C
  ISN 0003              COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                       1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                       2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
  ISN 0004              COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,
                       1 TVOLTS,CUR,XMETER
  ISN 0005              COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
  ISN 0006              COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE
  ISN 0007              COMMON/INTER/INT,IIA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,
                       1XI(30),YJ(20),ZK(10)
  ISN 0008              DIMENSION A(2),END1(2),END2(2),FATE(2)
  ISN 0009              DATA END1/4HABSO,4HRBED/,END2/4HESCA,4HPES /
  ISN 0010              XSAVE=XPT
  ISN 0011              YSAVE=YPT
  ISN 0012              TEMP= ABS(TVOLTS)
  ISN 0013              IF(TEMP.LE.0.) WRITE(M,999) TEMP
  ISN 0015        999   FORMAT(////1X, 38HTROUBLE - NEGATIVE OR ZERO TEMPERATURE)
  ISN 0016              IF(TEMP.LE.0.) RETURN
  ISN 0018              IF(MA.EQ.0.OR.ME.EQ.0) EE=EV/TEMP
  ISN 0020              PI=3.1415926536
  ISN 0021              A(1)=-1./SQRT(3.)
  ISN 0022              A(2)=-A(1)
  ISN 0023              MOSTPS=0
  ISN 0024              MSTEP=1000
                  C
                  C SET UP SUMS OVER TRAJECTORIES
                  C
  ISN 0025              IF(MA.EQ.0) GO TO 250
  ISN 0027              JAMAX=2
  ISN 0028              JBMAX=2
  ISN 0029              KAMAX=MA
  ISN 0030              KBMAX=MB
  ISN 0031              NUMBER=MA*MB*4
  ISN 0032              IF(NN.EQ.1) WRITE(M,990) MA,MB,NUMBER
  ISN 0034        990   FORMAT(/1X,I4,16H ALPHA-INTERVALS,3X,I4,15H BETA-INTERVALS,6X,
                       1 5HHENCE,I4,35H TRAJECTORIES FOR EACH ENERGY-VALUE)
                  C
  ISN 0035              IF(ME.EQ.0) GO TO 200
  ISN 0037              ME2=2*ME
  ISN 0038              JEMAX=2
  ISN 0039              KEMAX=ME
  ISN 0040              IF(NN.EQ.1) WRITE(M,988) ME,ME2
  ISN 0042        988   FORMAT(1X,I4,27H ENERGY INTERVALS AND HENCE,I4,14H ENERGY VALUES)
                  C
  ISN 0043              GO TO 300
                  C
                  C SINGLE VALUE OF ENERGY
                  C
  ISN 0044        200   JEMAX=1
  ISN 0045              KEMAX=1
  ISN 0046              IF(NN.EQ.1) WRITE(M,986) EV,EE
  ISN 0048        986   FORMAT(1X,31H MONOENERGETIC CASE WTIH ENERGY,1PE16.4,30H VOLTS, OR
                       1 DIMENSIONLESS VALUE,E16.4)
```

```
               C
ISN 0049                GO TO 300
               C
               C  SINGLE TRAJECTORY ONLY
               C
ISN 0050       250      JAMAX=1
ISN 0051                JBMAX=1
ISN 0052                JEMAX=1
ISN 0053                KAMAX=1
ISN 0054                KBMAX=1
ISN 0055                KEMAX=1
ISN 0056                AL=AL1*PI/180.
ISN 0057                BE=BE1*PI/180.
ISN 0058                WRITE(M,984) AL1,AL,BE1,BE,EV,EE
ISN 0059       984      FORMAT(/1X,17HSINGLE TRAJECTORY
                       1/1X, 7HALPHA =,F20.8 ,12H DEGREES, OR,F20.8 , 8H RADIANS
                       2/1X, 7HBETA  =,F20.8 ,12H DEGREES, OR,F20.8 , 8H RADIANS
                       3/1X, 8HENERGY =,1PE16.4,30H VOLTS, OR DIMENSIONLESS VALUE,E16.4)
ISN 0060                SINA=SIN(AL)
ISN 0061                COSA=COS(AL)
               C
               C  SUM OVER ENERGY, BETA, AND ALPHA
               C
ISN 0062          300   CONTINUE
ISN 0063                DENST=0.
ISN 0064                DO 1001 KE=1,KEMAX
ISN 0065                DO 1001 JE=1,JEMAX
ISN 0066                DENS=0.
ISN 0067                NOESC=0
ISN 0068                DO 1000 KB=1,KBMAX
ISN 0069                DO 1000 JB=1,JBMAX
ISN 0070                DO 1000 KA=1,KAMAX
ISN 0071                DO 1000 JA=1,JAMAX
               C
               C  INITIAL POSITION
               C
ISN 0072                Z=0.
ISN 0073                X=XSAVE
ISN 0074                Y=YSAVE
ISN 0075                IF(MA.EQ.0) GO TO 320
               C
ISN 0077                CA=(A(JA) + FLOAT(2*KA - 1 - MA))/FLOAT(MA)
ISN 0078                SINA=SQRT(.5*(1.+CA))
ISN 0079                COSA=SQRT(1. - SINA**2)
               C
ISN 0080                CBETA=(A(JB) + FLOAT(2*KB - 1 - MB))/FLOAT(MB)
ISN 0081                BE=PI*(1. + CBETA)
               C
               C
ISN 0082       320      XDOT=SINA*COS(BE)
ISN 0083                YDOT=SINA*SIN(BE)
ISN 0084                ZDOT=COSA
ISN 0085                INT=0
ISN 0086                CALL INTERP
               C
ISN 0087                IF(IGOUT.GE.1.AND.IGOUT.LE.IIA.AND.JGOUT.GE.1.AND.JGOUT.LE.JJA.
                       1 AND.KGOUT.GE.1.AND.KGOUT.LE.KKA) GO TO 340
ISN 0089       330      WRITE (M,9999)
```

```
ISN 0090      9999  FORMAT(/////1X,43HONE OF THE IG-JG-KG INDICES IS OUT OF RANGE)
ISN 0091            WRITE (M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0092            WRITE(M,982)KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0093            STOP
              C
ISN 0094      340   INT=1
ISN 0095            PHISAV=PHI
ISN 0096            SPEED=0.
ISN 0097            PHIOLD=PHI
ISN 0098            IF(ME.GT.0) GO TO 350
              C
ISN 0100            E=EE
ISN 0101            GO TO 400
              C
ISN 0102      350   CE=(A(JE) + FLOAT(2*KE-1-ME))/FLOAT(ME)
ISN 0103            E=(1.+CE)/(1.-CE)
ISN 0104            IF(XMACH.GT.1.) E=XMACH**2*(1.+CE)/(1.-CE)
ISN 0106            E=E + AMAX1(PHI, 0.)
              C
ISN 0107      400   IF(E.LT.PHI) GO TO 1001
ISN 0109            SPEED=SQRT(E-PHI)
              C
ISN 0110            XDOT=SPEED*SINA*COS(BE)
ISN 0111            YDOT=SPEED*SINA*SIN(BE)
ISN 0112            ZDOT=SPEED*COSA
ISN 0113            AL=ARCOS(COSA)
ISN 0114            AL1=AL*180./PI
ISN 0115            BE1=BE*180./PI
ISN 0116            EV=E*TEMP
ISN 0117            PVOLTS=PHISAV*TVOLTS
ISN 0118            ZOLD=Z
ISN 0119            KSTEP=0
ISN 0120            IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 490
              C
              C PRINT INITIAL CONDITIONS OF TRAJECTORY
              C
ISN 0122            WRITE(M,982) KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0123      982   FORMAT(/1X,52HKE,JE,  KB,JB,  KA,JA,  BETA,ALPHA,ENERGY,POTENTIAL=
                   1,/1X,3(I3,I2),1PE22.8 ,4H DEG,4X,E22.8 ,4H DEG,8X,E16.4,2H V,4X,
                   2 E16.4,2H V)
              C
ISN 0124            WRITE(M,980)
ISN 0125      980   FORMAT( 9X, 95HSTEPS      X              Y              Z          XDOT
                   1 YDOT          ZDOT          IG     JG     KG    PHI)
              C
ISN 0126            WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0127      888   FORMAT( 9X,I5,1P6E11.3,3I6,E11.3)
              C
              C     TAKE A STEP
              C
ISN 0128      490   IF (KSTEP.EQ.0) GO TO 550
ISN 0130      500   CALL ORBIT
ISN 0131            KSTEP=KSTEP + 1
ISN 0132            IF(NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
                   1 JGOUT,KGOUT,PHI
ISN 0134            IF(KSTEP.LE.MSTEP) GO TO 550
ISN 0136            WRITE(M,998) MSTEP
ISN 0137      998   FORMAT(/////1X, 9HMORE THAN,I6,19H STEPS - HENCE STOP)
```

```
ISN 0138            STOP
              C
              C
ISN 0139      550   IF(Z.EQ.0..AND.ZDOT.LT.0.
                   1.AND.Y.GE.YP(1).AND.Y.LE.YP(JV)) GO TO 600
              C
ISN 0141            IF((X.LE.XX(1).AND.ZDOT.LT.0.).OR.
                   1(X.GE.XX(II).AND.ZDOT.LT.0.))GO TO 600
              C
ISN 0143            IF((X.LE.XX(1).AND.XDOT.LT.0..AND.ZDOT.GT.0.).OR.
                   1   (Y.LE.YY(1).AND.YDOT.LT.0.).OR.
                   2(X.GE.XX(II).AND.XDOT.GE.0..AND.ZDOT.GT.0.).OR.
                   3   (Y.GE.YY(JJ).AND.YDOT.GT.0.).OR.
                   4   (Z.GE.ZZ(KK).AND.ZDOT.GT.0.))GO TO 700
              C
ISN 0145            IF(SKPRFL.EQ.1) GO TO 538
ISN 0147            IF(((Y.LE.(YY(MBC)-.5*Z)).AND.(Y.GT.(YY(MBC)-.5*ZZ(KUK)))).OR.
                   1((Y.GE.(YY(MBD)+.5*Z)).AND.(Y.LT.(YY(MBD)+.5*ZZ(KUK))))
                   2.AND.X.GE.XX(ILX).AND.X.LE.XX(IUX)) GO TO 600
ISN 0149      538   CONTINUE
ISN 0150            IF (Z.NE.0..OR .ZDOT.GE.0.) GO TO 540
ISN 0152            ZDOT=-ZDOT
ISN 0153            IF (NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
                   1 JGOUT,KGOUT,PHI
ISN 0155            GO TO 590
ISN 0156      540   CONTINUE
              C
ISN 0157            IF (KSTEP.EQ.0) GO TO 500
ISN 0159            PHIOLD=PHI
ISN 0160            CALL INTERP
ISN 0161            IF(IGOUT.LT.1.OR.IGOUT.GT.IIA.OR.JGOUT.LT.1.OR.JGOUT.GT.JJA.OR.
                   1KGOUT.LT.1.OR.KGOUT.GT.KKA) GO TO 330
ISN 0163            IF(NTIME.LT.1.OR.NTIME.GT.6) GO TO 580
              C
ISN 0165            IF(NTIME.NE.1.AND.NTIME.NE.2) GO TO 560
ISN 0167            XDOTS=XDOT**2 + PHIOLD-PHI
ISN 0168            IF(XDOTS.EQ.0.) XDOT=0.
ISN 0170            IF(XDOTS.GT.0..AND.XDOT.NE.0.) XDOT=SQRT(XDOTS)*SIGN(1.,XDOT)
ISN 0172            IF(XDOTS.LT.0..AND.XDOT.NE.0.) XDOT=-XDOT
ISN 0174            IF(NPRINT.EQ.3.AND.XDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
                   1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
              C
ISN 0176      560   IF(NTIME.NE.3.AND.NTIME.NE.4) GO TO 570
ISN 0178            YDOTS=YDOT**2 + PHIOLD-PHI
ISN 0179            IF(YDOTS.EQ.0.) YDOT=0.
ISN 0181            IF(YDOTS.GT.0..AND.YDOT.NE.0.) YDOT=SQRT(YDOTS)*SIGN(1.,YDOT)
ISN 0183            IF(YDOTS.LT.0..AND.YDOT.NE.0.) YDOT=-YDOT
ISN 0185            IF(NPRINT.EQ.3.AND.YDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
                   1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
              C
ISN 0187      570   IF(NTIME.NE.5.AND.NTIME.NE.6) GO TO 590
ISN 0189            ZDOTS=ZDOT**2 + PHIOLD-PHI
ISN 0190            IF(ZDOTS.EQ.0.) ZDOT=0.
ISN 0192            IF(ZDOTS.GT.0..AND.ZDOT.NE.0.) ZDOT=SQRT(ZDOTS)*SIGN(1.,ZDOT)
ISN 0194            IF(ZDOTS.LT.0..AND.ZDOT.NE.0.) ZDOT=-ZDOT
ISN 0196            IF(NPRINT.EQ.3.AND.ZDOTS.LT.0) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,
                   1 ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0198            GO TO 590
```

y< 0 *.5(z)

```
                C
ISN 0199        580    WRITE(M,997) NTIME
ISN 0200        997    FORMAT(////1X,17HTROUBLE - NTIME =,I3,19H = OUT OF RANGE 1-6)
ISN 0201               WRITE(M,887) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI,SAVE
ISN 0202        887    FORMAT( 9X,I5,1P6E11.3,3I6,E11.3,'SAVE=',E18.10)
ISN 0203               STOP
                C
ISN 0204        590    CALL INTERP
ISN 0205               IF(IGOUT.LT.1.OR.IGOUT.GT.IIA.OR.JGOUT.LT.1.OR.JGOUT.GT.JJA.OR.
                      1KGOUT.LT.1.OR.KGOUT.GT.KKA) GO TO 330
ISN 0207               IF(NPRINT.EQ.3) WRITE(M,888) KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,
                      1 JGOUT,KGOUT,PHI
ISN 0209               GO TO 500
                C
                C PARTICLE IS ABSORBED
ISN 0210        600    CONTINUE
ISN 0211               IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 1002
ISN 0213               FATE(1)=END1(1)
ISN 0214               FATE(2)=END1(2)
ISN 0215               GO TO 750
                C
                C PARTICLE ESCAPES
                C
ISN 0216        700    CONTINUE
ISN 0217               IF(NPRINT.EQ.1) GO TO 720
ISN 0219               IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 740
ISN 0221               FATE(1)=END2(1)
ISN 0222               FATE(2)=END2(2)
ISN 0223               GO TO 740
ISN 0224        720    WRITE(M,982) KE,JE,KB,JB,KA,JA,BE1,AL1,EV,PVOLTS
ISN 0225        740    NOESC=NOESC + 1
ISN 0226               IF(ME.EQ.0) GO TO 750
                C
ISN 0228               CSANGL=ZDOT/SQRT(XDOT**2+YDOT**2+ZDOT**2)
ISN 0229               XPON=-2.*XMACH*SQRT(E)*CSANGL - E - XMACH**2
ISN 0230               COEFA=SPEED**2/FLOAT(NUMBER)
ISN 0231               IF(ABS(XPON).GT.36.) GO TO 1000
ISN 0233               ADD =COEFA*EXP(XPON)
ISN 0234               DENS=DENS + ADD
                C
ISN 0235        750    IF(NPRINT.NE.2.AND.NPRINT.NE.3) GO TO 1002
ISN 0237               WRITE(M,889) FATE,KSTEP,X,Y,Z,XDOT,YDOT,ZDOT,IGOUT,JGOUT,KGOUT,PHI
ISN 0238        889    FORMAT(1X,2A4,I5,1P6E11.3,3I6,E11.3)
                C
ISN 0239        1002   CONTINUE
ISN 0240               IF(MOSTPS.GE.KSTEP) GO TO 1000
ISN 0242               KES=KE
ISN 0243               JES=JE
ISN 0244               KBS=KB
ISN 0245               JBS=JB
ISN 0246               KAS=KA
ISN 0247               JAS=JA
ISN 0248               MOSTPS=KSTEP
ISN 0249        1000   CONTINUE
                C
                C END OF SUM OVER ANGLES
                C
ISN 0250               FRACT=FLOAT(NOESC)/FLOAT(NUMBER)
```

```
                C
ISN 0251              WRITE(M,978) NOESC,NUMBER,FRACT,EV,DENS
ISN 0252        978   FORMAT(/1X,16HRATIO ESCAPING =,I5, 7H OUT OF,I5,14H OR A FRACTION,
                     1 F13.8,14H AT ENERGY E =,F13.8, 6H VOLTS,4X,6H(DENS=,1PE14.4,1H))
                C
ISN 0253              IF(NPRINT.EQ.0) GO TO 800
ISN 0255              IF(ME.NE.0) WRITE(M,976)
ISN 0257        976   FORMAT(1X,80HDENS IS THE SUM OF ADD=SPEED**2*EXP(XPON)/NUMBER OVER
                     1 A HEMISPHERE OF DIRECTIONS//)
                C
ISN 0258        800   IF(ME.EQ.0) GO TO 1001
ISN 0260              COEFE=2./(1. - CE)**2/FLOAT(ME)
ISN 0261              IF(XMACH.GT.1.) COEFE=COEFE*XMACH**2
ISN 0263              DENST=DENST + COEFE*DENS
ISN 0264        1001  CONTINUE
                C
ISN 0265              IF(ME.EQ.0) DENST=SPEED**2*FRACT
                C
                C     TRAJECTORY WITH MOST STEPS. PRINT K AND J INDICES.
                C
ISN 0267              WRITE(M,972) MOSTPS,KES,JES,KBS,JBS,KAS,JAS
ISN 0268        972   FORMAT(///1X,I5,3(I3,I2),29H =MOSTPS, KE,JE, KB,JB, KA,JA)
ISN 0269              WRITE(M,974) XSAVE,YSAVE,PHISAV,DENST,PARTCL
ISN 0270        974   FORMAT(/1X,26HAT DIMENSIONLESS X,Y,PHI =,3F12.6,1H,,5X,1PE16.4,
                     1  33H = NORMALIZED CURRENT DENSITY FOR,2A5//)
ISN 0271              RETURN
ISN 0272              END
```

```
        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
  ISN 0002                 SUBROUTINE INTERP
                C
                C          INTERPOLATION WITHIN GRID
                C
  ISN 0003                 COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                          1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                          2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
  ISN 0004                 COMMON/ORB/XDOT,YDOT,ZDOT,X1,X2,Y1,Y2,Z1,Z2,X,Y,Z,PHI,NTIME,SAVE
  ISN 0005                 COMMON/INTER/INT,IIA,JJA,KKA,IGOUT,JGOUT,KGOUT,XA,YA,ZA,
                          1XI(30),YJ(20),ZK(10)
                C
  ISN 0006                 IGOUT=0
  ISN 0007                 JGOUT=0
  ISN 0008                 KGOUT=0
  ISN 0009                 NCH=0
                C
  ISN 0010                 XA=X
  ISN 0011                 YA=Y
  ISN 0012                 ZA=Z
                C
                C          LOCATE XA
                C
  ISN 0013                 IF(XA.EQ.XI(IIA)) IG=IIA-1
  ISN 0015                 IF(XA.EQ.XI(IIA)) GO TO 103
  ISN 0017                 IF(INT.NE.0)      GO TO 100
                C
  ISN 0019                 DO 10 I=2,IIA
  ISN 0020                 IG=I-1
  ISN 0021                 IF(XA.LT.XI(I))   GO TO 103
  ISN 0023      10         CONTINUE
                C
  ISN 0024      100        IF(XA.GE.XI(IG+1)) GO TO 102
  ISN 0026                 IF(XA.GE.XI(IG))   GO TO 104
  ISN 0028      101        IG=IG-1
  ISN 0029                 IF(XA.LT.XI(IG))   GO TO 101
  ISN 0031                 GO TO 103
  ISN 0032      102        IG=IG+1
  ISN 0033                 IF(XA.GE.XI(IG+1)) GO TO 102
                C
  ISN 0035      103        NCH=1
  ISN 0036      104        CONTINUE
                C
                C          ACCEPT IF XI(IG) LESS THAN OR EQUAL TO XA LESS THAN XI(IG+1).
                C
                C
                C          LOCATE YA
                C
  ISN 0037                 IF(YA.EQ.YJ(JJA)) JG=JJA-1
  ISN 0039                 IF(YA.EQ.YJ(JJA)) GO TO 203
  ISN 0041                 IF(INT.NE.0)      GO TO 200
                C
  ISN 0043                 DO 20 J=2,JJA
  ISN 0044                 JG=J-1
  ISN 0045                 IF(YA.LT.YJ(J))   GO TO 203
  ISN 0047      20         CONTINUE
                C
```

```
ISN 0048      200    IF(YA.GE.YJ(JG+1)) GO TO 202
ISN 0050             IF(YA.GE.YJ(JG))   GO TO 204
ISN 0052      201    JG=JG-1
ISN 0053             IF(YA.LT.YJ(JG))   GO TO 201
ISN 0055             GO TO 203
ISN 0056      202    JG=JG+1
ISN 0057             IF(YA.GE.YJ(JG+1)) GO TO 202
              C
ISN 0059      203    NCH=1
ISN 0060      204    CONTINUE
              C
              C      ACCEPT IF YJ(JG) LESS THAN OR EQUAL TO YA LESS THAN YJ(JG+1).
              C
              C
              C      LOCATE ZA
              C
ISN 0061             IF(ZA.EQ.ZK(KKA)) KG=KKA-1
ISN 0063             IF(ZA.EQ.ZK(KKA)) GO TO 303
ISN 0065             IF(INT.NE.0)      GO TO 300
              C
ISN 0067             DO 30 K=2,KKA
ISN 0068             KG=K-1
ISN 0069             IF(ZA.LT.ZK(K))    GO TO 303
ISN 0071      30     CONTINUE
              C
ISN 0072      300    IF(ZA.GE.ZK(KG+1)) GO TO 302
ISN 0074             IF(ZA.GE.ZK(KG))   GO TO 304
ISN 0076      301    KG=KG-1
ISN 0077             IF(ZA.LT.ZK(KG))   GO TO 301
ISN 0079             GO TO 303
ISN 0080      302    KG=KG+1
ISN 0081             IF(ZA.GE.ZK(KG+1)) GO TO 302
              C
ISN 0083      303    NCH=1
ISN 0084      304    CONTINUE
              C
              C      ACCEPT IF ZK(KG) LESS THAN OR EQUAL TO ZA LESS THAN ZK(KG+1).
              C
              C      LOCATE LINE AND BOX
              C
ISN 0085             X1=XI(IG)
ISN 0086             Y1=YJ(JG)
ISN 0087             Z1=ZK(KG)
ISN 0088             X2=XI(IG+1)
ISN 0089             Y2=YJ(JG+1)
ISN 0090             Z2=ZK(KG+1)
              C
ISN 0091             IF(X.NE.X1.OR.XDOT.GE.0.) GO TO 400
ISN 0093             IG=IG-1
ISN 0094             X2=X1
ISN 0095             X1=XI(IG)
              C
ISN 0096      400    IF(Y.NE.Y1.OR.YDOT.GE.0.) GO TO 500
ISN 0098             JG=JG-1
ISN 0099             Y2=Y1
ISN 0100             Y1=YJ(JG)
              C
ISN 0101      500    IF(Z.NE.Z1.OR.ZDOT.GE.0.) GO TO 600
```

```
ISN 0103          KG=KG-1
ISN 0104          Z2=Z1
ISN 0105          Z1=ZK(KG)
            C
ISN 0106    600   PHI=VV(IG,JG,KG)
ISN 0107          IGOUT=IG
ISN 0108          JGOUT=JG
ISN 0109          KGOUT=KG
ISN 0110          RETURN
ISN 0111          END
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,                     DATE
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002              SUBROUTINE POWER
               C
               C  CURRENT DENSITIES AND POWER LOSS
               C
ISN 0003              COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                     1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                     2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004              COMMON/CP/NPRINT,NPTS,MA,MB,ME,KMAX,XPT,YPT,AL1,BE1,EV,SMACH,
                     1 TVOLTS,CUR,XMETER
ISN 0005              COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
ISN 0006              DIMENSION A(2)
ISN 0007              IF(NPTS.EQ.0.OR.MA.EQ.0) WRITE(M,997) XPT,YPT,AL1,BE1,EV
ISN 0009       997    FORMAT(/1X,  9HX AND Y =,2F10.5,20X,19HALPHA,BETA,ENERGY =,3F20.5)
ISN 0010              IF(NPRINT.EQ.0) WRITE(M,990)
ISN 0012              IF(NPRINT.EQ.1) WRITE(M,991)
ISN 0014              IF(NPRINT.EQ.2) WRITE(M,992)
ISN 0016              IF(NPRINT.EQ.3) WRITE(M,993)
ISN 0018       990    FORMAT(/38H NPRINT=0 MEANS NO TRAJECTORY PRINTING)
ISN 0019       991    FORMAT(/53H NPRINT=1 PRINT INDICES OF ESCAPING TRAJECTORIES ONLY)
ISN 0020       992    FORMAT(/56H NPRINT=2 PRINT FIRST AND LAST STEPS OF ALL TRAJECTORIE
                     1S)
ISN 0021       993    FORMAT(/52H NPRINT=3 MEANS PRINT EVERY STEP OF ALL TRAJECTORIES)
               C
ISN 0022              IF(TVOLTS.EQ.0.) RETURN
               C
ISN 0024              XMACH=SMACH
               C
               C  NON-DIMENSIONALIZE THE POTENTIAL DISTRIBUTION.  THEN RESTORE AT END.
               C
ISN 0025              DO 200 K=1,KK
ISN 0026              DO 200 J=1,JJ
ISN 0027              DO 200 I=1,II
ISN 0028              VV(I,J,K )=VV(I,J,K)/TVOLTS
ISN 0029       200    CONTINUE
               C
               C  DEFINE THE PANEL POINTS AT WHICH THE CURRENT AND POWER IS EVALUATED
               C
               C  CASE OF A SINGLE POINT
               C
ISN 0030              IF(NPTS.EQ.0.OR.MA.EQ.0) COEFM = XMETER**2
               C
               C  CASE OF MULTIPLE POINTS FOR INTEGRATION OVER PANEL SUB-AREAS
               C
ISN 0032              JVM=1
ISN 0033              IVM=1
ISN 0034              IF(JV.GT.1) JVM=JV-1
ISN 0036              IF(IV.GT.1) IVM=IV-1
ISN 0038              NA=0
ISN 0039              NAREAS=IVM*JVM
ISN 0040              TPOWER=0.
ISN 0041              TCURNT=0.
ISN 0042              TAREA=0.
ISN 0043              NN=0
ISN 0044              DO 500 J=1,JVM
ISN 0045              DO 500 I=1,IVM
ISN 0046              NA=NA+1
```

```
ISN 0047             NP=0
ISN 0048             IF(NPTS.EQ.0.OR.MA.EQ.0) GO TO 250
ISN 0050             PO = 0
ISN 0051             CU = 0
ISN 0052             A(1)=-1./SQRT(3.)
ISN 0053             A(2)=-A(1)
ISN 0054             GO TO 260
ISN 0055       250   CONTINUE
ISN 0056             JXMAX=1
ISN 0057             JYMAX=1
ISN 0058             KMAX=1
ISN 0059             GO TO 270
ISN 0060       260   JXMAX=2
ISN 0061             JYMAX=2
ISN 0062       270   CONTINUE
ISN 0063             DO 400 KY=1,KMAX
ISN 0064             DO 400 KX=1,KMAX
ISN 0065             DO 400  JY=1,JYMAX
ISN 0066             DO 400  JX=1,JXMAX
ISN 0067             NP=NP+1
ISN 0068             NN=NN+1
ISN 0069             IF(NPTS.EQ.0.OR.MA.EQ.0) GO TO 300
ISN 0071             CX=(A(JX) + FLOAT(2*KX - 1 - KMAX))/FLOAT(KMAX)
ISN 0072             CY=(A(JY) + FLOAT(2*KY - 1 - KMAX))/FLOAT(KMAX)
ISN 0073             XPT=(XP(I+1)-XP(I))/2.*CX + (XP(I+1)+XP(I))/2.
ISN 0074             YPT = (YP(J+1)-YP(J))/2.*CY + (YP(J+1)+YP(J))/2.
ISN 0075             COEF = (XP(I+1)-XP(I))*(YP(J+1)-YP(J))
ISN 0076             AREA = COEF * XMETER**2
ISN 0077             COEFM = AREA/4./FLOAT(KMAX**2)
               C
               C
               C COMPUTE EACH CURRENT DENSITY AND MULTIPLY BY LOCAL POTENTIAL TO
               C EVALUATE POWER DENSITY
ISN 0078       300   CALL DEN
ISN 0079             DENCUR=DENST*CUR
ISN 0080             POWDEN=PVOLTS*DENCUR
ISN 0081             IF(MA.EQ.0) GO TO 600
ISN 0083             XPTM=XPT*XMETER
ISN 0084             YPTM=YPT*XMETER
ISN 0085             XPM=XP(I)*XMETER
ISN 0086             XPPM=XP(I+1)*XMETER
ISN 0087             YPM=YP(J)*XMETER
ISN 0088             YPPM=YP(J+1)*XMETER
               C
ISN 0089       995   FORMAT (6X,12HAT POINT NO.,I3,10H, WITH X =,F10.5,13H METERS,  Y =
                    1,F10.5,27H METERS,  AND COEFFICIENT =,F10.5,14H SQUARE METERS)
               C
ISN 0090             IF(NPTS.GT.0.AND.MA.GT.0) WRITE(M,994) NA,XPM,XPPM,YPM,YPPM
ISN 0092       994   FORMAT( /5X,16H IN SUB-AREA NO.,I3,1X,17HBOUNDED BY X IN (,
                    1 F10.5,3H TO,F10.5, 9H) METERS,,4X,13HAND BY Y IN (,
                    2 F10.5,3H TO,F10.5, 8H) METERS)
               C
ISN 0093             WRITE (M,995) NP,XPTM,YPTM,COEFM
ISN 0094             WRITE(M,988) PVOLTS,DENCUR,POWDEN,PARTCL
ISN 0095       988   FORMAT(6X,53HTHE VOLTAGE, CURRENT DENSITY, AND POWER DENSITY ARE =
                    1/6X,1PE16.4,6H VOLTS,4X,E16.4,23H AMP/(SQ-METER),    AND,E16.4,
                    2 24H WATT/(SQ-METER),     FOR,2A5//)
ISN 0096             IF(NPTS.EQ.0) GO TO 600
```

4·x4x4x4x2x

LTRJ = NN/(MA·MB·ME·9

NIMB = . 3.8 *

LTRJCT = NN/NIMB

```
ISN 0098          CU = CU + COEFM*DENCUR
ISN 0099          PO = PO + COEFM * POWDEN
ISN 0100    400   CONTINUE
ISN 0101          AVCD = CU/AREA
ISN 0102          AVPD = PO/AREA
            C
ISN 0103          WRITE(M,986) NA,CU,PO,PARTCL
ISN 0104          WRITE(M,984) NA,AREA,AVCD,AVPD
ISN 0105    984   FORMAT(  1X,18HIN SUB-AREA NUMBER,I3,8H OF AREA,1PE16.4,15H SQUARE
                 1 METERS,/52H THE AVERAGE CURRENT DENSITY AND POWER DENSITY ARE =,
                 2 E16.4,19H AMP/(SQ-METER) AND,E16.4,16H WATT/(SQ-METER))
ISN 0106    986   FORMAT( /1X,18HIN SUB-AREA NUMBER,I3,28H THE CURRENT AND POWER ARE
                 1 =,1PE16.4,12H AMP,      AND,E16.4,14H WATTS,      FOR,2A5)
            C
ISN 0107          TAREA=TAREA + AREA
ISN 0108          TCURNT = TCURNT + CU
ISN 0109          TPOWER = TPOWER + PO
ISN 0110    500   CONTINUE
            C
ISN 0111          WRITE(M,982) TCURNT,TPOWER,PARTCL
ISN 0112    982   FORMAT(///1X,34HTOTAL CURRENT AND POWER LOSS ARE =,1PE16.4,
                 1 12H AMP,      AND,E16.4,13H WATT,      FOR,2A5)
ISN 0113          AVCD=TCURNT/TAREA
ISN 0114          AVPD=TPOWER/TAREA
ISN 0115          WRITE(M,980) TAREA,AVCD,AVPD
ISN 0116    980   FORMAT(/1X,26HWITH A TOTAL PANEL AREA OF,1PE16.4,15H SQUARE METERS
                 1,/1X,51HTHE AVERAGE CURRENT DENSITY AND POWER DENSITY ARE =,
                 2 E16.4,19H AMP/(SQ-METER) AND,E16.4,16H WATT/(SQ-METER))
            C
            C
            C     RESTORE POTENTIAL DISTRIBUTION TO DIMENSIONAL VALUES
            C
ISN 0117      600 CONTINUE
ISN 0118          DO 700 K=1,KK
ISN 0119          DO 700 J=1,JJ
ISN 0120          DO 700 I=1,II
ISN 0121          VV(I,J,K)=VV(I,J,K)*TVOLTS
ISN 0122    700   CONTINUE
ISN 0123          RETURN
ISN 0124          END
```

```
       COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002                SUBROUTINE LIST(LST,IP)
ISN 0003                COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                       1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                       2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004                COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005                DIMENSION KOUT(5),XOUT(5),YOUT(5),ZOUT(5)
ISN 0006                DO 500 LINE=1,60
ISN 0007                DO 200 NP=1,5
ISN 0008                KP=LINE + (NP-1)*60 + (IP-1) * 300
ISN 0009                IF(KP.GT.NTOT.AND.NP.EQ.1) RETURN
ISN 0011                IF(KP .GT. NTOT) GO TO 300
ISN 0013                NMAX=NP
ISN 0014                KOUT(NP) = KP
ISN 0015                IF(LST.EQ.1) XOUT(NP) = X(KP,1)
ISN 0017                IF(LST .EQ. 2) XOUT(NP) =XYZ(KP,1)
ISN 0019                IF(LST .EQ. 2) YOUT(NP)=XYZ(KP,2)
ISN 0021                IF(LST .EQ. 2) ZOUT(NP) =XYZ(KP,3)
ISN 0023          200   CONTINUE
ISN 0024          300   GO TO (400,450),LST
ISN 0025          400   WRITE(M,1000) (KOUT(NP),XOUT(NP), NP=1,NMAX)
ISN 0026          1000  FORMAT(5(I8,F16.8))
ISN 0027                GO TO 500
ISN 0028          450   WRITE(M,3000) (KOUT(NP),XOUT(NP),YOUT(NP),ZOUT(NP),NP=1,NMAX)
ISN 0029          3000  FORMAT(5(I8,3F6.2))
ISN 0030          500   CONTINUE
ISN 0031                RETURN
ISN 0032                END
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002                  SUBROUTINE RELAX
                C         POINT-SUCCESSIVE OVERRELAXATION METHOD
ISN 0003                  COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                         1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                         2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004                  COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005                  OMEGA=1.9
ISN 0006                  EPS = 1.E-3
ISN 0007                  ITMAX=2000
ISN 0008                  ITR=0
ISN 0009                  IPROLD=0
ISN 0010                  IGO=1
ISN 0011        200       ITR=ITR+1
ISN 0012                  DELTAM=0.
ISN 0013                  DO 500 N=1,NTOT
ISN 0014                  IF(X(N,2).EQ.1)GO TO 500
ISN 0016                  X1=X(N,1)
                C
ISN 0017                  FN=COEF(N,1)/COEF(N,7)
ISN 0018                  FS=COEF(N,2)/COEF(N,7)
ISN 0019                  FE=COEF(N,3)/COEF(N,7)
ISN 0020                  FW=COEF(N,4)/COEF(N,7)
ISN 0021                  FU=COEF(N,5)/COEF(N,7)
ISN 0022                  FD=COEF(N,6)/COEF(N,7)
                C
ISN 0023                  NN=INDX(N,1)
ISN 0024                  NS=INDX(N,2)
ISN 0025                  NE=INDX(N,3)
ISN 0026                  NW=INDX(N,4)
ISN 0027                  NU=INDX(N,5)
ISN 0028                  ND=INDX(N,6)
                C
ISN 0029                  SUM=0.
ISN 0030                  IF(NN.GT.0) SUM = SUM+FN*X(NN,1)
ISN 0032                  IF(NS.GT.0) SUM = SUM+FS*X(NS,1)
ISN 0034                  IF(NE.GT.0) SUM = SUM+FE*X(NE,1)
ISN 0036                  IF(NW.GT.0) SUM = SUM+FW*X(NW,1)
ISN 0038                  IF(ND.GT.0) SUM = SUM+FD*X(ND,1)
ISN 0040                  IF(NU.GT.0) SUM = SUM+FU*X(NU,1)
                C
ISN 0042                  X(N,1) = OMEGA*SUM+(1.-OMEGA)*X1
ISN 0043                  DELTA = ABS(X(N,1)-X1)
ISN 0044                  IF(ABS(X1).GT.1.E-10) DELTA=ABS((X(N,1)-X1)/X1)
ISN 0046                  IF(DELTA .GT. DELTAM) DELTAM=DELTA
ISN 0048        500       CONTINUE
ISN 0049                  IF(ITR.GT.ITMAX) WRITE(M,8888) ITR
ISN 0051                  IF(ITR.GT.ITMAX) GO TO 700
ISN 0053        8888      FORMAT(////10H MORE THAN, I4,11H ITERATIONS)
ISN 0054                  IPR=ITR/500
ISN 0055                  IF(IPR.LE.IPROLD) GO TO 600
ISN 0057                  IPROLD=IPR
ISN 0058                  GO TO 800
                C
ISN 0059        600       IF(DELTAM.GT.EPS) GO TO 200
                C
                C         ITERATION FINISHED.  PRINT AND EXIT.
```

```
                C
ISN 0061        700    IGO=2
ISN 0062        800    NFPP=(NTOT/300) +1
ISN 0063               DO 900 IP=1,NFPP
ISN 0064               WRITE(M,7777) ITR,EPS,DELTAM,OMEGA
ISN 0065        7777   FORMAT(15H1SOLUTION AFTER,I6,2X,25HITERATIONS WITH TOLERANCE,
                      1 F12.8,8X,18HMAXIMUM DIFFERENCE,F12.8,8X,6HOMEGA=,F8.5)
ISN 0066               CALL LIST(1,IP)
ISN 0067        900    CONTINUE
                C
ISN 0068               GO TO (600,1000),IGO      IF(IGO.EQ.1) GO TO 600
ISN 0069        1000   RETURN
ISN 0070               END
```

LEVEL 21.8 (JUN 74)   OS/360 FORTRAN H

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
 ISN 0002            SUBROUTINE FIND(I,J,K)
 ISN 0003            COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                    1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                    2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
 ISN 0004            IIJJ=II*JJ
 ISN 0005            K=N/IIJJ+1
 ISN 0006            IF(K .GE. 2 .AND. MOD(N,IIJJ) .EQ. 0) K=K-1
 ISN 0008            NKIJ=N - IIJJ*(K-1)
 ISN 0009            J=NKIJ/II+1
 ISN 0010            IF(J .GE. 2 .AND. MOD(NKIJ,II) .EQ. 0) J=J-1
 ISN 0012            I=NKIJ - II*(J-1)
 ISN 0013            RETURN
 ISN 0014            END
```

```
         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002                 SUBROUTINE ARRAY
ISN 0003                 COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                        1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                        2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004                 COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005                 COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
               C
               C         COEFFICIENT ARRAY = COEF(N,7), WHERE
               C         COEF(N,1)=CN  (NORTH=+Y NEIGHBOR)
               C         COEF(N,2)=CS  (SOUTH=-Y NEIGHBOR)
               C         COEF(N,3)=CE  ( EAST=+X NEIGHBOR)
               C         COEF(N,4)=CW  ( WEST=-X NEIGHBOR)
               C         COEF(N,5)=CU  (    UP=+Z NEIGHBOR)
               C         COEF(N,6)=CD  ( DOWN=-Z NEIGHBOR)
               C         COEF(N,7)=CC  (       = CENTRAL POINT)
               C
               C         SAVE COEFFICIENTS AND INDICES
               C
ISN 0006                 COEF(N,1)=CN
ISN 0007                 COEF(N,2)=CS
ISN 0008                 COEF(N,3)=CE
ISN 0009                 COEF(N,4)=CW
ISN 0010                 COEF(N,5)=CU
ISN 0011                 COEF(N,6)=CD
ISN 0012                 COEF(N,7)=CC
               C
ISN 0013                 INDX(N,1)=NN
ISN 0014                 INDX(N,2)=NS
ISN 0015                 INDX(N,3)=NE
ISN 0016                 INDX(N,4)=NW
ISN 0017                 INDX(N,5)=NU
ISN 0018                 INDX(N,6)=ND
ISN 0019                 IF(SKPCO.EQ.1) GO TO 20
ISN 0021                 WRITE(M,1000) ND,CD,NS,CS,NW,CW,N,CC,NE,CE,NN,CN,NU,CU
ISN 0022       1000      FORMAT(/7(1X,1H(,I4,2H)=,1PE10.4))
ISN 0023         20      CONTINUE
ISN 0024                 RETURN
ISN 0025                 END
```

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                                   OS/360  FORTRAN H
                                                                                DATE
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                               SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002             SUBROUTINE CUD(MP,C,A)
ISN 0003             COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                    1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                    2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004             COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
ISN 0005             NF(IX,JX,KX) = IX+II*(JX-1) + II*JJ*(KX-1)
ISN 0006             A=0.
ISN 0007             C=0.
ISN 0008             CALL FIND(I,J,K)
ISN 0009             IF(I .EQ. 1) GO TO 100
ISN 0011             IF(I .EQ. II) GO TO 200
ISN 0013             NH=NF(I+1,J,K)
ISN 0014             NL=NF(I-1,J,K)
ISN 0015             DX=XYZ(NH,1) - XYZ(NL,1)
ISN 0016             GO TO 300
ISN 0017      100    NH=NF(2,J,K)
ISN 0018             DX=XYZ(NH,1) - XYZ(N,1)
ISN 0019             GO TO 300
ISN 0020      200    NL=NF(II-1,J,K)
ISN 0021             DX=XYZ(N,1) - XYZ(NL,1)
ISN 0022      300    CONTINUE
ISN 0023             IF(J .EQ. 1) GO TO 400
ISN 0025             IF(J .EQ. JJ) GO TO 500
ISN 0027             NH=NF(I,J+1,K)
ISN 0028             NL=NF(I,J-1,K)
ISN 0029             DY=XYZ(NH,2) - XYZ(NL,2)
ISN 0030             GO TO 600
ISN 0031      400    NH=NF(I,2,K)
ISN 0032             DY=XYZ(NH,2) - XYZ(N,2)
ISN 0033             GO TO 600
ISN 0034      500    NL=NF(I,JJ-1,K)
ISN 0035             DY=XYZ(N,2) - XYZ(NL,2)
ISN 0036      600    A=DX*DY/4.
ISN 0037             IF(MP .EQ. 1) GO TO 700
ISN 0039             IF(MP .EQ. 2) GO TO 800
ISN 0041             RETURN
ISN 0042      700    NU=0
ISN 0043             IF(K .EQ. KK) RETURN
ISN 0045             NH=NF(I,J,K+1)
ISN 0046             NU=NH
ISN 0047             DZ=XYZ(NH,3) - XYZ(N,3)
ISN 0048              GO TO 900
ISN 0049      800    ND=0
ISN 0050             IF(K .EQ. 1) RETURN
ISN 0052             NL=NF(I,J,K-1)
ISN 0053             ND=NL
ISN 0054             DZ=XYZ(N,3) - XYZ(NL,3)
ISN 0055      900    C=A/DZ
ISN 0056             RETURN
ISN 0057             END
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
 ISN 0002                 SUBROUTINE CNS(MP,C,A)
 ISN 0003                 COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                         1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                         2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
 ISN 0004                 COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
 ISN 0005                 NF(IX,JX,KX)=IX+II*(JX-1)+II*JJ*(KX-1)
 ISN 0006                 A=0.
 ISN 0007                 C=0.
 ISN 0008                 CALL FIND(I,J,K)
 ISN 0009                 IF(I.EQ.1) GO TO 100
 ISN 0011                 IF(I.EQ.II) GO TO 200
 ISN 0013                 NH=NF(I+1,J,K)
 ISN 0014                 NL=NF(I-1,J,K)
 ISN 0015                 DX=XYZ(NH,1) - XYZ(NL,1)
 ISN 0016                 GO TO 300
 ISN 0017         100     NH=NF(2,J,K)
 ISN 0018                 DX=XYZ(NH,1) - XYZ(N,1)
 ISN 0019                 GO TO 300
 ISN 0020         200     NL=NF(II-1,J,K)
 ISN 0021                 DX=XYZ(N,1) - XYZ(NL,1)
 ISN 0022         300     CONTINUE
 ISN 0023                 IF(K.EQ.1) GO TO 400
 ISN 0025                 IF(K.EQ.KK) GO TO 500
 ISN 0027                 NH=NF(I,J,K+1)
 ISN 0028                 NL=NF(I,J,K-1)
 ISN 0029                 DZ=XYZ(NH,3) - XYZ(NL,3)
 ISN 0030                 GO TO 600
 ISN 0031         400     NH=NF(I,J,2)
 ISN 0032                 DZ=XYZ(NH,3) - XYZ(N,3)
 ISN 0033                 GO TO 600
 ISN 0034         500     NL=NF(I,J,KK-1)
 ISN 0035                 DZ=XYZ(N,3) - XYZ(NL,3)
 ISN 0036         600     A=DX*DZ/4.
 ISN 0037                 IF(MP.EQ.1) GO TO 700
 ISN 0039                 IF(MP.EQ.2) GO TO 800
 ISN 0041                 RETURN
 ISN 0042         700     NN=0
 ISN 0043                 IF(J.EQ.JJ) RETURN
 ISN 0045                 NH=NF(I,J+1,K)
 ISN 0046                 NN=NH
 ISN 0047                 DY=XYZ(NH,2) - XYZ(N,2)
 ISN 0048                 GO TO 900
 ISN 0049         800     NS=0
 ISN 0050                 IF(J.EQ.1) RETURN
 ISN 0052                 NL=NF(I,J-1,K)
 ISN 0053                 NS=NL
 ISN 0054                 DY=XYZ(N,2) - XYZ(NL,2)
 ISN 0055         900     C=A/DY
 ISN 0056                 RETURN
 ISN 0057                 END
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                         SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002               SUBROUTINE CEW(MP,C,A)
ISN 0003               COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                      1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                      2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004               COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
ISN 0005               NF(IX,JX,KX)= IX+ II*(JX-1) + II*JJ*(KX-1)
ISN 0006               A=0.
ISN 0007               C=0.
ISN 0008               CALL FIND(I,J,K)
ISN 0009               IF(J.EQ.1) GO TO 100
ISN 0011               IF(J .EQ. JJ) GO TO 200
ISN 0013               NH=NF(I,J+1,K)
ISN 0014               NL=NF(I,J-1,K)
ISN 0015               DY=XYZ(NH,2) - XYZ(NL,2)
ISN 0016               GO TO 300
ISN 0017         100   NH=NF(I,2,K)
ISN 0018               DY=XYZ(NH,2) - XYZ(N,2)
ISN 0019               GO TO 300
ISN 0020         200   NL=NF(I,JJ-1,K)
ISN 0021               DY=XYZ(N,2) - XYZ(NL,2)
ISN 0022         300   CONTINUE
ISN 0023               IF(K .EQ. 1) GO TO 400
ISN 0025               IF(K .EQ. KK) GO TO 500
ISN 0027               NH=NF(I,J,K+1)
ISN 0028               NL=NF(I,J,K-1)
ISN 0029               DZ=XYZ(NH,3) - XYZ(NL,3)
ISN 0030               GO TO 600
ISN 0031         400   NH=NF(I,J,2)
ISN 0032               DZ=XYZ(NH,3) - XYZ(N,3)
ISN 0033               GO TO 600
ISN 0034         500   NL=NF(I,J,KK-1)
ISN 0035               DZ=XYZ(N,3) - XYZ(NL,3)
ISN 0036         600   A=DY*DZ/4.
ISN 0037               IF(MP .EQ. 1) GO TO 700
ISN 0039               IF(MP .EQ. 2) GO TO 800
ISN 0041               RETURN
ISN 0042         700   NE=0
ISN 0043               IF(I.EQ.II) RETURN
ISN 0045               NH=NF(I+1,J,K)
ISN 0046               NE=NH
ISN 0047               DX=XYZ(NH,1) - XYZ(N,1)
ISN 0048               GO TO 900
ISN 0049         800   NW=0
ISN 0050               IF(I .EQ. 1) RETURN
ISN 0052               NL=NF(I-1,J,K)
ISN 0053               NW=NL
ISN 0054               DX=XYZ(N,1) - XYZ(NL,1)
ISN 0055         900   C=A/DX
ISN 0056               RETURN
ISN 0057               END
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                         SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF        DATE
ISN 0002            SUBROUTINE FIELD
             C
             C      CONSTRUCTION OF COEFFICIENTS (MATRIX ELEMENTS)
             C      IN LINEAR DIFFERENCE EQUATIONS
             C      SOLUTION BY OVERRELAXATION
             C
ISN 0003            COMMON/BK/IIM,IIP,JJM,JJP,KK,NTOT,IV,JV,II,JJ,M,N,VP(30),
                   1XYZ(2080,3),VV(30,20,10),XP(30),XM(10),YP(20),YM(10),ZZ(10),
                   2XX(40),YY(30),ILX,IUX,KUK,MBC,MBD,VRF,NFPS,SKPRFL,SKPLST
ISN 0004            COMMON/FLD/X(2080,2),COEF(2080,7),INDX(2080,6),SKPCO
ISN 0005            COMMON/CCC/CN,CS,CE,CW,CU,CD,CC,NN,NS,NE,NW,NU,ND
             C
ISN 0006            INTEGER OO,ON/'NORT'/,OS/'SOUT'/,OE/'EAST'/,OW/'WEST'/,
                   1 OU/'UP  '/,OD/'DOWN'/
             C      ASSUME ASYMPTOTIC MONOPOLE AT INFINITY
             C
ISN 0007            ALPHAF(UUU)=ABS(UUU/RS)
             C
             C      NDO=POSITIVE FOR DIAGNOSTIC OUTPUT
ISN 0008            NDO=0
             C
ISN 0009            WRITE(M,1000)
ISN 0010     1000   FORMAT(1H1/18HOFIELD CALCULATION)
ISN 0011            WRITE(M,2000)
ISN 0012     2000   FORMAT(////1X,17HCOEFFICIENT ARRAY)
ISN 0013            X0=.5*XP(IV)
ISN 0014            Y0=.5*YP(JV)
ISN 0015            ZOLD=0.
ISN 0016            DO 600 N=1,NTOT
ISN 0017            RS=(XYZ(N,1)-X0)**2 +(XYZ(N,2)-Y0)**2 +XYZ(N,3)**2
ISN 0018            CALL FIND (I,J,K)
ISN 0019            IF(ZZ(K).LE.ZOLD.AND.N.GT.1) GO TO 200
ISN 0021            ZOLD=ZZ(K)
ISN 0022            WRITE(M,3000) K,ZZ(K)
ISN 0023     3000   FORMAT(  //1X,2HZ(,I2,2H)=,F6.3/
                   1 12X,1HD,17X,1HS,17X,1HW,17X,1HC,17X,1HE,17X,1HN,17X,1HU)
ISN 0024     200    CC=0.
             C
             C   MODIFICATION TO SOLVE HELMHOLTZ EQUATION USING LINEARIZED SPACE
             C   CHARGE.   HELM = DEBYE-LENGTH-LIKE PARAMETER.  (ASSUMES POTEN-
             C   TIALS ARE DIMENSIONLESS)
             C
ISN 0025            HELM=0.0
ISN 0026            VOLSQ=1.
ISN 0027            DO 300 MP=1,2
ISN 0028            CALL CNS(MP,C,AREA)
ISN 0029            IF (MP.EQ.1) OO=ON
ISN 0031            IF (MP.EQ.2) OO=OS
ISN 0033            IF (NDO.GT.0) WRITE (M,888) N,I,J,K,OO,AREA,C
ISN 0035     888    FORMAT(1X,18HN,I,J,K,OO,AREA,C=,I4,2X,3I3,1X,A5,1P2E16.4)
ISN 0036            CC=CC+C
ISN 0037            IF(C.GT.0.) GO TO 250
ISN 0039            YYY=XYZ(N,2)-Y0
ISN 0040             ALPHA=ALPHAF(YYY)
ISN 0041            IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0043     999    FORMAT(1X,14HN,I,J,K,ALPHA=,I4,2X,3I3,1PE16.4)
```

```
ISN 0044             CC=CC+AREA*ALPHAF(YYY)
ISN 0045       250   IF(MP.EQ.1) CN=C
ISN 0047             IF(MP.EQ.2) CS=C
ISN 0049       300   CONTINUE
ISN 0050             VOLSQ=VOLSQ*AREA
ISN 0051             DO 400 MP=1,2
ISN 0052             CALL CEW(MP,C,AREA)
ISN 0053              IF (MP.EQ.1) DO=OE
ISN 0055              IF (MP.EQ.2) DO=OW
ISN 0057             IF (NDO.GT.0) WRITE (M,888) N,I,J,K,DO,AREA,C
ISN 0059             CC=CC+C
ISN 0060             IF(C.GT.0.) GO TO 350
ISN 0062             XXX=XYZ(N,1)-X0
ISN 0063              ALPHA=ALPHAF(XXX)
ISN 0064             IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0066             CC=CC+AREA*ALPHAF(XXX)
ISN 0067       350   IF(MP.EQ.1) CE=C
ISN 0069             IF(MP.EQ.2) CW=C
ISN 0071       400   CONTINUE
ISN 0072             VOLSQ=VOLSQ*AREA
ISN 0073             DO 500 MP=1,2
ISN 0074             CALL CUD(MP,C,AREA)
ISN 0075              IF (MP.EQ.1) DO=OU
ISN 0077              IF (MP.EQ.2) DO=OD
ISN 0079             IF (NDO.GT.0) WRITE (M,888) N,I,J,K,DO,AREA,C
ISN 0081             CC=CC+C
ISN 0082             IF(C.GT.0..OR.(C.EQ.0..AND.MP.EQ.2))GO TO 450
ISN 0084              ALPHA=ALPHAF(XYZ(N,3))
ISN 0085             IF (NDO.GT.0) WRITE (M,999) N,I,J,K,ALPHA
ISN 0087             CC=CC+AREA*ALPHAF(XYZ(N,3))
ISN 0088       450   IF(MP.EQ.1) CU=C
ISN 0090             IF(MP.EQ.2) CD=C
ISN 0092       500   CONTINUE
ISN 0093             VOLSQ=VOLSQ*AREA
ISN 0094             VOL=SQRT(VOLSQ)
ISN 0095             IF(HELM.GT.0.) CC=CC+VOL/HELM**2
ISN 0097             CALL ARRAY
ISN 0098       600   CONTINUE
               C
ISN 0099             CALL RELAX
ISN 0100             RETURN
ISN 0101             END
```

```
       COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002          BLOCK DATA
ISN 0003          COMMON/CD/PVOLTS,XMACH,DENST,NN,PARTCL(2),PART1(2),PART2(2)
ISN 0004          REAL PART1/'IONS','    '/,PART2/'ELEC','TRON'/
ISN 0005          END
```

Appendix B

Computer Programs: Electric Fields Produced by Cloud-to-Ground Lightning Flashes

The following four pages contain a listing of the computer programs written to compute the electric field produced on the ground as a function of time and distance from "ground zero" by the charges associated with a cloud-to-ground lightning flash. This program was written by Jerry L. Bohannon.

```
TITL CLOUD-TO-GROUND SIMULATION
BATCH
LAE= STROKE
DBUG
      IMPLICIT INTEGER*2 (I-N)
      DIMENSION RSI(2,10),RSIS(2,10)
      DATA TPIE/5.56062E-11/,TIPIM/2.0E-7/
      DATA ICARDS/'C'/,ITERM/'T'/,IY/'Y'/,IN/'N'/
      DATA IMA/X'1D15'/,ICY/X'1C16'/,IBEL/X'0707'/,IBG/X'1E10'/
      DATA IRD/X'1D11'/,IGR/X'1C12'/,IYE/X'1D13'/,IBL/X'1D14'/
      DATA IA7N/X'0E'/,IA7F/X'0F'/,NULL/X'00'/,IHOME/X'08'/
      DATA IBGY/X'1E13'/
      DATA RSI(1,1)/0.0/,RSI(2,1)/0.0/,RSI(2,10)/0.0/
      DATA PIE/3.1415926/
      DATA RHO/2.0E-9/
      CROOT=1./3.
      WRITE(14,1)
      FORMAT('1')
      DO 1000 I=1,32000
000   K=I
      WRITE(14,4) IA7N,IMA,IBEL,IA7F
      FORMAT(2A2,'LIGHTNING BOLT SIMULATION-- .RO1',2A2)
0     WRITE(14,11) IBL,IGR
1     FORMAT(A2,'READ DATA FROM CARDS OR TERMINAL',A2)
      READ(15,12) IWHERE
2     FORMAT(A1)
3     IF(IWHERE.EQ.ICARDS)GOTO 50
      IF(IWHERE.EQ.ITERM) GOTO 70
      WRITE(14,14) IRD,IRG
4     FORMAT(A2,'TRY AGAIN',A2)
      GOTO 10
0     READ(1,51,END=999) YO,QCL,QSL,VSL,VRS,((RSI(L,J),L=1,2),J=2,9)
1     FORMAT(5(F6.0,2X)/8(2F10.0/))
      GOTO 90
0     WRITE(14,71) IMA
1     FORMAT(A2,'ENTER FLOATING POINT INITIAL CONDITIONS  F6.0')
      WRITE(14,75) IBL,ICY
5     FORMAT(A2,'INITIAL HEIGHT  KM',A2)
      READ(15,73) YO
      WRITE(14,76) IBL,ICY
6     FORMAT(A2,'CLOUD CHARGE   COUL',A2)
      READ(15,73) QCL
      WRITE(14,72) IBL,ICY
2     FORMAT(A2,'STEPPED LEADER CHARGE  COUL',A2)
      READ(15,73) QSL
3     FORMAT(F6.0)
      WRITE(14,74) IBL,ICY
4     FORMAT(A2,'STEPPED LEADER VELOCITY  E5 M/S',A2)
      READ(15,73) VSL
      WRITE(14,77) IBL,ICY
7     FORMAT(A2,'RETURN STROKE VELOCITY  E7 M/S',A2)
      READ(15,73) VRS
3     WRITE(14,80) IBL,ICY
)     FORMAT(A2,'ENTER 8 TIMES (MS) AND CURRENTS (KAMP) TO DEFINE THE'/
     *'RETURN STROKE  2F10.0'/' !',19X,' !',A2)
      DO 82 J=2,9
      READ(15,81) RSI(1,J),RSI(2,J)
      IF(RSI(1,J).LT.0.) GOTO 78
      CONTINUE
```

```
81    FORMAT(2F10.0)
90    VSLS=VSL
      RSI(1,10)=RSI(1,9)
      DO 1002 J=1,10
      RSIS(1,J)=RSI(1,J)
      RSIS(2,J)=RSI(2,J)
      RSI(1,J)=RSI(1,J)/1000.
      RSI(2,J)=RSI(2,J)*1000.
1002  CONTINUE
      QCL=-QCL
      QSL=-QSL
      YOS=YO
      RAD=(0.75*ABS(QCL)/RHO/PIE)**CROOT
      DO 1005 I=2,9
      A=RSI(2,I)
      B=RSI(2,I-1)
      C=RSI(2,I+1)
      IF(A.GT.B.AND.A.GT.C) IQT=I
1005  CONTINUE
      VRSS=VRS
100   VSL=-VSL*1.0E5
      YO=YO*1000.0
      VRS=VRS*1.0E7
      DTSL=1.0E-4
105   WRITE(14,110) IBL,ICY
110   FORMAT(A2,'WHAT IS RADIUS',A2)
      READ(15,73) D
      WRITE(13,111) IRD,IBGY
111   FORMAT(2A2/'1')
      DO 1001 I=1,32000
1001  K=I
      WRITE(13,149)
 149  FORMAT(1X,'SI UNITS'//)
150   WRITE(13,151) YOS,QCL,QSL,VSLS,VRSS,RSIS,D
151   FORMAT(1X,'HEIGHT= ',F7.0,' KM'/1X,'Q-CLOUD= ',F7.1,' C'/
     $1X,'Q-LEADER= ',F6.1,' C'/1X,'V-LEADER= ',F6.1,' E5 M/S'/1X,
     $ 'V-RETURN= ',F6.1,' E7 M/S'/1X,' RETURN STROKE MS. KAMP'/
     $10(2F10.4/)/1X,'RADIUS= ',F6.0,' M'///)
      WRITE(13,152) IRG,IRD
 52   FORMAT(1X,
     $A2,8X,'T',15X,'E',15X,'Q',16X,'H',A2)
      T=0.0
      SLRY2=1.0/(D*D+YO*YO)
      SLRY=SQRT(SLRY2)
      YC=YO+RAD
      SLRQC2=1.0/(D*D+YC*YC)
      SLRQCL=SQRT(SLRQC2)*SLRQC2
      DI=1.0/D
      X=YO
      EMAX=0.0
 00   CONTINUE
      SLRX2=1.0/(D*D+X*X)
      SLRX=SQRT(SLRX2)
      SLRX32=SLRX*SLRX2
      E=QSL/TPIE/YO*(SLRX-SLRY)+SLRQCL*YC/TPIE*(QCL-QSL*(1.-X/YO))
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(ABS(E).LT.5.0E4) GOTO 211
      WRITE(13,210)T,E,X
 10   FORMAT(F16.7,F16.0,16X,F16.1)
```

```
215   FORMAT(F16.7, F16.0, F16.5,F16.1,I10,F16.7,F16.0)
211   IF(ABS(E).LT.5.0E4.OR.X.GT.0.5E3) DTSL=1.0E-3
      T=T+DTSL
      IF(X.LT.50.) GOTO 500
      X=YO+VSL*T
      IF(X.LT.0.0) GOTO 500
      DTSL=1.0E-4
      GOTO 200
500   CONTINUE
      T=T-DTSL
      WRITE(13,501)
501   FORMAT(1X,' ')
      ESL=E
      QRC=QSL-QCL
      PL=-QSL/YO
      SLRY03=YC*SLROCL
      KRNT=1
      RI=0.0
      TR=0.0
      KOLD=0
      Q=0.0
510   CONTINUE
      CALL CURENT(RSI,Q,DT,TR,RI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      Y=VRS*TR
      IF(Y.GT.YO) GOTO 522
      P=Q/Y
      SLRYR=1.0/SQRT(D*D+Y*Y)
      E=ESL+P*(DI-SLRYR)/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(IQT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 510
      WRITE(13,215) T,E,Q,Y,KRNT,TR,RI
      GOTO 510
22    WRITE(13,501)
20    CONTINUE
      P=Q/YO
      IF(P.GT.PL) GOTO 572
      E=ESL+P*(DI-SLRY)/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(IQT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 521
      WRITE(13,215) T,E,Q,YO,KRNT,TR,RI
21    CALL CURENT(RSI,Q,DT,TR,RI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      GOTO 520
72    WRITE(13,501)
70    CONTINUE
      QRS=Q+QSL
      IF(QRS.GT.QRC) GOTO 600
      E=ESL+PL*(DI-SLRY)/TPIE+QRS*SLRY03/TPIE
      IF(ABS(E).GT.ABS(EMAX)) EMAX=E
      IF(IQT.LT.KRNT.AND.ABS(E).LT.5.0E4) GOTO 571
      WRITE(13,215) T,E,Q,YC,KRNT,TR,RI
1     CALL CURENT(RSI,Q,DT,TR,RI,KRNT,KOLD)
      IF(RI.LE.0.0) GOTO 600
      T=T+DT
      GOTO 570
0     WRITE(13,599) Q ,EMAX
```

```
99    FORMAT(//1X,'CRT= ',F10.4,' C',5X,'EMAX= ',E12.4,' V/M')
      WRITE(14,601) IBG,IBL,IGR,IBEL
01    FORMAT(2A2,'DO YOU WANT ANOTHER RADIUS',2A2)
02    READ(15,12) IAD
      IF(IAD.EQ.IY) GOTO 1.5
      IF(IAD.EQ.IN) GOTO 650
      WRITE(14,14) IRD,IGR
      GOTO 602
50    WRITE(14,651) IBL,IGR
51    FORMAT(A2,'DO YOU WANT ANOTHER EVENT',A2)
52    READ(15,12) IE
      IF(IE.EQ.IY) GOTO 13
      IF(IE.EQ.IN) GOTO 95
      WRITE(14,14) IRD,IGR
      GOTO 652
99    WRITE(14,998) IRD
98    FORMAT(A2,'NO MORE CARDS')
50    WRITE(14,951) IMA,IGR
51    FORMAT(A2,'END OF PROGRAM',A2)
      STOP 1
      END
LAB=  CURENT
DBUG
      SUBROUTINE CURENT(RSI,Q,DT,TR,RI,KRNT,KOLD)
      IMPLICIT INTEGER*2 (I-N)
      DIMENSION RSI(2,10)
      IF(KOLD.EQ.KRNT) GOTO 50
      TAU=RSI(1,KRNT+1)-RSI(1,KRNT)
      IF(TAU.LE.0.0) GOTO 100
      IF(TAU.LE.1.0E-5) DT=0.5E-6
      IF(TAU.GT.1.0E-5.AND.TAU.LE.1.0E-4) DT=1.0E-5
      IF(TAU.GT.1.0E-4.AND.TAU.LE.1.0E-3) DT=1.0E-4
      IF(TAU.GT.1.0E-3.AND.TAU.LE.1.0E-2) DT=1.0E-3
      IF(TAU.GT.1.0E-2.AND.TAU.LE.1.0E-1) DT=1.0E-2
      IF(TAU.GT.1.0E-1) DT=0.025
      DELI=(RSI(2,KRNT+1)-RSI(2,KRNT))/TAU
      IF(Q.EQ.0.0) RI1=0.0
      TRR=TR+DT
      IF(TRR.GT.RSI(1,KRNT+1)) DT=RSI(1,KRNT+1)-TR
      RI=RI+DELI*DT
      RI2=RI
      Q=Q+DT*(RI2+RI1)/2.
      TR=TR+DT
      KOLD=KRNT
      IF(TR.GE.RSI(1,KRNT+1)) KRNT=KRNT+1
      RI1=RI2
      RETURN
10    CONTINUE
      RI=0.0
      RETURN
      END
END
```

<u>Appendix C</u>

Computer Output Listing: Cloud-to-Ground Lightning Flash Density

The following seven pages are the computed output from the program that calculates the lightning flash density (cloud-to-ground) from the monthly thunderstorm days using the Pierce Conversion. This program, written by Jerry L. Bohannon, uses the Normals, Means and Extremes data from "Local Climatological Data -- Annual Summaries for 1977" published by the National Oceanic and Atmospheric Administration, Environmental Data Service, Asheville, North Carolina (available also on magnetic tape).

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∇COMPUPOT [⎕]∇
∇ AAR←WID COMPUPOT HI
[1]  ⍝    THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL IN A REGION ARROUND
[2]  ⍝ ONE BILLBOARD OF THE RECTENNA.  THE MEASUREMENT AREA STARTS 31.96 METERS
[3]  ⍝ FROM THE LEFT HAND EDGE OF THE RECTENNA AND EXTENDS TO THE RIGHT 'AC' METERS.
[4]  ⍝ THE BOTTOM  OF THE MEASUREMENT AREA IS AT GROUND LEVEL, WHILE THE TOP
[5]  ⍝ IS 'UP' METERS HIGH.
[6]  ⍝    THE RESOLUTION IS CONTROLLED BY THE ARGUMENTS OF THE FUNCTION.  THE
[7]  ⍝ LEFT ARGUMENT SPECIFIES THE NUMBER OF COLUMNS IN THE OUTPUT.  THE RIGHT
[8]  ⍝ ARGUMENT IS THE NUMBER OF ROWS.
[9]  ⍝    THE FORMAT OF THE OUTPUT IS AN ARRAY OF NUMBERS IN SCIENTIFIC NOTATION
[10] ⍝ WITH ONLY ONE SIGNIFICANT DIGIT PRINTED.
[11]  POT←(HI,WID)⍴0
[12]  ⎕PP←1
[13]  Q←R←1
[14] LOOPH:H1←(Q-1)×UP÷HI-1
[15]  R←1
[16] LOOPL:L1←31.96+(R-1)×AC÷WID-1
[17]  POT[Q;R]←L1 FIELD H1
[18]  R←R+1
[19]  →(R≤WID)/LOOPL
[20]  Q←Q+1
[21]  →(Q≤HI)/LOOPH
[22]  TRY←TRY+1
[23]  DA←1⌽3↑⎕TS.
[24]  'THIS IS RUN NUMBER ',(⍕TRY),DATE
[25]  'THE CALCULATED VALUES OF THE ELECTRIC POTENTIAL, IN VOLTS, ARE SHOWN BELOW.'
[26]  ''
[27]  ''
[28]  AAR←POT←⊖POT
[29]  5⍴⎕AV[201]·
[30]  ⎕PP←10
[31]  'THE VECTOR OF LINE CHARGES USED IS... ',(⍕LA),' COULOMBS PER METER.'
[32]  'THE SUM OF THE LINE CHARGES IS ',(⍕+/LA),' COULOMBS PER METER.'
[33]  'THE TOP OF THE MEASUREMENT ARRAY IS ',(⍕UP),' METERS HIGH.'
[34]  'THE RIGHT EDGE OF THE ARRAY IS ',(⍕L1),' METERS FROM THE FIRST BILLBOARD.'
[35]  'THERE ARE ',(⍕AC÷WID),' COLUMNS PER METER, AND ',(⍕UP÷HI),' ROWS PER METER IN THE ARRAY.'
[36]  'RUN NO. ',(⍕TRY),DATE
[37]  ⎕PP←1
[38]  5⍴⎕AV[201]
[39]  →(SIGN=0)/0
[40]  'THE ARRAY BELOW SHOWS THE SIGN OF EACH OF THE NUMBERS IN THE ABOVE ARRAY.'
[41]  ''
[42]  ×POT
[43]  'THIS IS RUN NUMBER ',(⍕TRY),DATE
∇
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∇PROTECT [⎕]∇
∇ WID PROTECT HI
[1]  ⍝    THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL IN A REGION OF SPACE
[2]  ⍝ DUE TO A CHARGED WIRE LOCATED SOME FIXED PERPENDICULAR DISTANCE FROM
[3]  ⍝ THE TOP OF EACH BILLBOARD OF THE RECTENNA.  THE MEASUREMENT AREA IS
[4]  ⍝ EXACTLY THE SAME AS THAT USED IN ((COMPUPOT)).  AS WITH ((COMPUPOT))
[5]  ⍝ THE RESOLUTION IS DETERMINED BY THE ARGUMENTS OF THE FUNCTION.
[6]  ⍝    THE FUNCTION DOES NOT PRINT ANY OUTPUT.  THE OUTPUT IS CONTAINED IN
[7]  ⍝ THE VARIABLE, ((PROT)).  THIS VARIABLE WILL HAVE THE SAME DIMENTIONS AS
[8]  ⍝ ((POT)), THE VARIABLE CONTAINING THE OUTPUT FROM ((COMPUPOT)).
[9]   PROT←(HI,WID)⍴0
[10]  Q1←R1←1
[11] ⍝  ((LOOPH)) COMPUTES ALL OF THE VERTICAL INDICES.
[12] LOOPH:H2←(Q1-1)×UP÷HI-1
[13]  R1←1
[14] ⍝   ((LOOPL)) COMPUTES THE HORIZONTAL INDICES AND CALLS ((FIELDW)).
[15] LOOPL:L2←31.96+(R1-1)×AC÷WID-1
[16]  PROT[Q1;R1]←L2 FIELDW H2
[17]  R1←R1+1
[18]  →(R1≤WID)/LOOPL
[19]  Q1←Q1+1
[20]  →(Q1≤HI)/LOOPH
[21]  PROT←⍉PROT
[22]  TRY1←TRY1+1
[23]  'THIS IS RUN NUMBER ',(⍕TRY1),' OF PROTECT',DATE
[24]  ⎕PP←10
[25]  'THE PROTECTING WIRE IS LOCATED ',(⍕XJ1),' METERS FROMT THE'
[26]  'LEFT EDGE OF THE ARRY, AND ',(⍕S1×XJ1),' METERS FROM THE BOTTOM.'
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      ∇FIELD [⎕]∇
      ∇ UHL←L FIELD H
[1]   ⍝    THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL AT ANY POINT, (L,H)
[2]   ⍝ IN THE SPACE AROUND THE ARRAY OF FIVE BILLBOARDS.
[3]    LI←15.93×¯1+⍳N
[4]    XJ←(9.38×⍳N)÷N←⍴LA
[5]    S←3○○2÷9
[6]    A←L-XJ
[7]    I←1
[8]    UI←N⍴0
[9]   BBLOOP:NM←((H-S×XJ)*2)+NA←(A-LI[I])*2
[10]   DM←((H+S×XJ)*2)+NA
[11]   UI[I]←+/-(LA÷○2×E0)×⍟(NM÷DM)*0.5
[12]   I←I+1
[13]   →(I<N+1)/BBLOOP
[14]   UHL←(¯100000×H)++/UI
      ∇
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      ∇FIELDW [⎕]∇
      ∇ P←L FIELDW H
[1]   ⍝    THIS FUNCTION COMPUTES THE ELECTRIC POTENTIAL AT ANY POINT, (L,H),
[2]   ⍝ DUE TO THE CHARGED PROTECTION WIRE ABOVE THE BILLBOARD.  THIS WIRE IS
[3]   ⍝ ASSUMED TO BE PARALLEL TO THE BILLBOARD AND LOCATED A PERPENDICULAR
[4]   ⍝ DISTANCE, <<SPACE>>, FROM THE TOP OF THE BILLBOARD.
[5]   ⍝    THE CHARGE ON THE WIRE IS <<LW>>.
[6]    LI1←15.93×¯1+⍳N
[7]    N←⍴LW←,LW
[8]    LONG←12.24÷2○THTA←¯3○(÷12.24)×SPACE
[9]    XJ1←,XJ1←LONG×2○THTA+○2÷9
[10]   S1←3○(○2÷9)+THTA
[11]   A1←L-XJ1
[12]   I←1
[13]   UI1←N⍴0
[14]  LOOP:NM1←((H-S1×XJ1)*2)+NA1←(A1-LI1[I])*2
[15]   DM1←((H+S1×XJ1)*2)+NA1
[16]   UI1[I]←+/-(LW÷○2×E0)×⍟(NM1÷DM1)*0.5
[17]   I←I+1
[18]   →(I<N+1)/LOOP
[19]   P←+/UI1
      ∇
```

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND STRIKE DENSITY (NO./YR./KM^2)
AL	BIRMINGHAM	58.71	13.87
AL	HUNTSVILLE	59.20	13.34
AL	MOBILE	79.78	27.07
AL	MONTGOMERY	62.18	15.44
AK	ANCHORAGE	1.12	0.39
AK	ANNETTE	1.45	0.60
AK	BARROW	0.07	0.06
AK	BARTER ISLAND	0.26	0.17
AK	BETHEL	1.39	0.51
AK	BETTLES	4.67	0.78
AK	BIG DELTA	2.60	0.41
AK	COLD BAY	0.05	0.04
AK	FAIRBANKS	5.12	0.83
AK	GULKANA	4.70	0.76
AK	HOMER	0.38	0.15
AK	JUNEAU	0.32	0.24
AK	KING SALMON	1.31	0.48
AK	KODIAK	0.29	0.09
AK	KOTZEBUE	0.52	0.24
AK	MC GRATH	6.77	1.05
AK	NOME	0.42	0.19
AK	ST PAUL ISLAND	0.05	0.05
AK	SHEYMA ISLAND	0.15	0.10
AK	SUMMIT	5.00	0.32
AK	TALKEETNA	4.30	0.77
AK	UNAKLEET	1.90	0.46
AK	YAKUTAT	1.59	0.60
AZ	FLAGSTAFF	50.63	15.87
AZ	PHOENIX	23.03	4.60
AZ	TUCSON	39.84	13.29
AZ	WINSLOW	36.34	9.83
AZ	YUMA	7.26	1.43
AR	FORT SMITH	57.06	11.84
AR	LITTLE ROCK	56.97	11.51
AS	PAGO PAGO	26.09	3.73
CA	BAKERSFIELD	2.80	0.95
CA	BISHOP	13.24	2.21
CA	BLUE CANYON	11.83	1.97
CA	EUREKA	4.55	1.23
CA	FRESNO	5.43	1.37
CA	LONG BEACH	3.71	1.10
CA	LOS ANGLES (CITY)	6.21	1.43
CA	LOS ANGLES (LAX)	3.51	1.10
CA	MOUNT SHASTA	13.27	2.16
CA	OAKLAND	2.28	0.87
CA	RED BLUFF	9.70	1.52
CA	SACRAMENTO	4.75	1.27

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM^2)
CA	SANDBERG	4.22	1.14
CA	SAN DIEGO	2.70	0.96
CA	SAN FRANCISCO (CITY)	2.25	0.88
CA	SAN FRANCISCO (SFO)	2.12	0.55
CA	STOCKTON	3.11	1.01
CA	SANTA MARIA	2.32	0.89
CO	ALAMOSA	44.42	12.92
CO	COLORADO SPRINGS	59.69	22.43
CO	DENVER	41.33	11.02
CO	GRAND JUNCTION	34.32	6.38
CO	PUEBLO	40.32	10.99
CT	BRIDGEPORT	21.57	3.50
CT	HARTFORD	22.30	3.62
DE	WILMINGTON	31.03	5.73
DC	WASHINGTON (DCA)	29.07	5.18
DC	WASHINGTON (IAD)	27.13	4.60
FL	APALACHICOLA	70.19	22.99
FL	DAYTONA BEACH	79.61	29.25
FL	FORT MYERS	94.67	47.04
FL	JACKSONVILLE	63.94	20.26
FL	KEY WEST	52.66	19.38
FL	LAKELAND	99.50	48.56
FL	MIAMI	74.04	26.37
FL	ORLANDO	81.21	32.79
FL	ORLANDO (MC COY AFB)	78.62	30.37
FL	PENSACOLA	74.13	22.90
FL	TALLAHASSEE	86.37	35.05
FL	TAMPA	88.19	40.90
FL	WEST PALM BEACH	78.63	28.69
GA	ATHENS	51.52	13.00
GA	ATLANTA	50.19	11.57
GA	AUGUSTA	56.15	15.41
GA	COLUMBUS	58.71	15.61
GA	MACON	56.83	15.43
GA	ROME	61.42	15.87
GA	SAVANNAH	64.33	20.62
GU	TAGUAC	27.09	4.79
HI	HILO	8.75	1.67
HI	HONOLULU	7.07	1.48
HI	KAHULUI	4.95	1.20
HI	LIHUI	8.81	1.64

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND-STRIKE DENSITY (NO./YR./KM²)
ID	BOISE	14.34	2.34
ID	LEWISTON	15.75	2.45
ID	POCATELLO	23.11	4.02
IL	CAIRO	52.77	10.95
IL	CHICAGO (MIDWAY)	40.54	7.53
IL	CHICAGO (O'HARE)	38.42	6.92
IL	MOLINE	47.36	10.01
IL	PEORIA	48.94	10.25
IL	ROCKFORD	42.19	8.38
IL	SPRINGFIELD	50.00	10.79
IN	EVANSVILLE	45.73	8.87
IN	FORT WAYNE	41.00	7.87
IN	INDIANAPOLIS	44.69	8.37
IN	SOUTH BEND	42.39	8.64
IA	BURLINGTON	50.58	11.05
IA	DES MOINES	49.73	11.22
IA	DUBUQUE	44.93	9.29
IA	SIOUX CITY	45.38	10.49
IA	WATERLOO	41.70	8.51
KS	CONCORDIA	58.93	15.71
KS	DODGE CITY	53.03	14.32
KS	GOODLAND	48.74	13.69
KS	TOPEKA	57.58	14.14
KS	WICHITA	55.29	13.25
KY	LEXINGTON	46.76	10.22
KY	LOUISVILLE	45.40	9.13
LA	ALEXANDRIA	68.07	16.95
LA	BATON ROUGE	70.46	20.07
LA	LAKE CHARLES	76.88	22.59
LA	NEW ORLEANS	68.93	20.38
LA	SHREVEPORT	54.16	10.21
ME	CARIBOU	20.33	3.67
ME	PORTLAND	18.05	2.95
MD	BALTIMORE	28.44	5.10
MA	BOSTON	19.33	3.14
MA	NANTUCKET	20.27	3.09
MA	WORCESTER	21.27	3.51

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM^2)
MI	ALPENA	33.29	6.25
MI	DETROIT (DTT)	32.02	5.67
MI	DETROIT (DTW)	33.26	5.07
MI	FLINT	33.03	5.97
MI	GRAND RAPIDS	36.71	6.50
MI	HOUGHTON LAKE	38.54	7.65
MI	LANSING	34.17	6.18
MI	MARQUETTE	28.07	5.03
MI	MUSKEGON	37.34	6.83
MI	SAULT STE MARIE	29.44	5.22
MN	DULUTH	34.66	7.38
MN	INTERNATIONAL FALLS	31.42	5.67
MN	MINNEAPOLIS	36.79	7.41
MN	ROCHESTER	41.00	8.32
MN	SAINT CLOUD	35.76	7.54
MS	JACKSON	65.79	16.30
MS	MERIDAN	58.59	13.31
MO	COLUMBIA	51.50	10.40
MO	KANSAS CITY (MCI)	51.20	11.39
MO	KANSAS CITY (MKC)	49.66	10.59
MO	SAINT JOSEPH	56.35	13.76
MO	ST. LOUIS	44.55	8.61
MO	SPRINGFIELD	58.00	13.00
MT	BILLINGS	28.79	6.00
MT	GLASGOW	27.11	5.30
MT	GREAT FALLS	25.60	5.17
MT	HAVRE	21.60	3.86
MT	HELENA	33.51	8.32
MT	KALISPELL	22.75	3.96
MT	MILES CITY	28.43	6.02
MT	MISSOULA	23.61	4.36
NE	GRAND ISLAND	47.99	11.76
NE	LINCOLN (APT)	48.33	10.77
NE	LINCOLN (CITY)	49.33	11.99
NE	NORFOLK	50.20	13.11
NE	NORTH PLATTE	45.92	11.95
NE	OMAHA (CITY)	40.50	8.00
NE	OMAHA (EPPLY FIELD)	48.60	11.26
NE	SCOTTSBLUFF	43.56	11.92
NE	VALENTINE	45.22	12.79
NV	ELKO	20.72	3.47
NV	ELY	32.00	6.75
NV	LAS VEGAS	14.97	2.05
NV	RENO	13.54	2.06
NV	WINNEMUCCA	14.36	2.24

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUNDSTRIKE DENSITY (NO./YR./KM^2)
NH	CONCORD	20.47	3.49
NH	MT WASHINGTON	15.33	2.74
NJ	ATLANTIC CITY	25.47	4.36
NJ	NEWARK	25.47	4.40
NJ	TRENTON	33.22	6.03
NM	ALBUQUERQUE	42.34	11.18
NM	CLAYTON	54.11	17.03
NM	ROSWELL	32.60	6.30
NY	ALBANY	27.64	5.20
NY	BINGHAMTON	31.42	5.94
NY	BUFFALO	30.74	5.18
NY	NEW YORK (CITY)	19.47	3.16
NY	NEW YORK (JFK)	22.32	3.56
NY	NEW YORK (LA GUARDIA)	24.24	4.01
NY	ROCHESTER	29.24	5.21
NY	SYRACUSE	29.39	5.43
NC	ASHEVILLE	49.00	12.18
NC	CAPE HATTERAS	44.75	9.23
NC	CHARLOTTE	41.39	9.35
NC	GREENSBORO	46.57	11.50
NC	RALEIGH	45.67	10.67
NC	WILMINGTON	40.12	10.92
ND	FARGO	32.33	6.98
ND	BISMARK	33.58	7.99
ND	WILLISTON	26.77	5.65
OH	AKRON	40.41	8.13
OH	CINCINNATI (ABBE OBS)	50.41	11.52
OH	CINCINNATI (APT)	44.23	9.15
OH	CLEVELAND	35.42	6.65
OH	COLUMBUS	42.45	8.93
OH	DAYTON	40.32	7.85
OH	TOLEDO	40.00	8.11
OH	MANSFIELD	39.78	7.73
OH	YOUNGSTOWN	35.85	6.68
OK	OKLAHOMA CITY	50.68	10.84
OK	TULSA	52.25	11.21
OR	ASTORIA	7.67	1.52
OR	BURNS	13.85	2.02
OR	EUGENE	4.30	1.25
OR	MEACHAM	15.70	2.37
OR	MEDFORD	8.52	1.53

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND-STRIKE DENSITY (NO./YR./KM^2)
OR	PENDLETON	9.90	1.64
OR	PORTLAND	5.86	1.46
OR	SALEM	5.50	1.32
OR	SEXTON SUMMIT	5.70	1.20
PA	ALLENTOWN	32.82	6.31
PA	AVOCA	31.05	5.86
PA	ERIE	33.36	5.91
PA	HARRISBURG	32.79	6.34
PA	PHILADELPHIA	26.81	4.66
PA	PITTSBURG	35.28	6.80
PA	WILLIAMSPORT	34.29	7.11
PR	SAN JUAN	39.73	7.92
RI	BLOCK ISLAND	15.79	2.68
RI	PROVIDENCE	20.42	3.27
SC	CHARLESTON	56.45	16.63
SC	COLUMBIA	54.27	14.73
SC	GREER	43.37	9.54
SD	ABERDEEN	35.08	8.13
SD	HURON	40.34	9.53
SD	RAPID CITY	42.42	12.17
SD	SIOUX FALLS	43.69	10.23
TN	BRISTOL	45.50	10.55
TN	CHATTANOOGA	56.11	13.95
TN	KNOXVILLE	47.83	10.36
TN	MEMPHIS	52.93	10.28
TN	NASHVILLE	55.42	12.42
TN	OAK RIDGE	52.81	12.71
TX	ABILENE	41.73	7.65
TX	AMARILLO	48.81	12.29
TX	AUSTIN	40.31	6.71
TX	BROWNSVILLE	24.34	3.72
TX	CORPUS CHRISTI	30.76	4.69
TX	DALLAS-FT WORTH (DFW)	45.12	8.04
TX	DALLAS (LOVE FIELD)	40.15	5.62
TX	DEL RIO	35.36	6.39
TX	EL PASO	35.89	8.99
TX	HOUSTON	57.50	17.92
TX	LUBBOCK	45.32	10.12
TX	MIDLAND-ODESSA	36.45	5.76
TX	PORT ARTHUR	64.17	16.71
TX	SAN ANGELO	36.60	6.32
TX	SAN ANTONIO	36.00	5.74
TX	VICTORIA	45.13	9.91

STATE	STATION	THUNDERSTORM DAYS (NO./YEAR)	GROUND-STRIKE DENSITY (NO./YR./KM^2)
TX	WACO	45.44	7.82
TX	WICHITA FALLS	48.85	9.30
TT	JOHNSTON ISLAND	4.07	1.17
TT	KOROR ISLAND	36.65	5.46
TT	KWAJALEIN ISLAND	9.76	1.78
TT	MAJURO ATOLL	16.52	2.58
TT	PONAPE ISLAND	28.04	3.97
TT	TRUK ATOLL	19.42	2.62
TT	WAKE ISLAND	6.93	1.30
TT	YAP ISLAND	16.03	2.46
UT	MILFORD	32.06	7.33
UT	SALT LAKE CITY	35.29	6.84
UT	WENDOVER	29.00	5.77
VT	BURLINGTON	24.94	4.63
VA	LYNCHBURG	40.50	9.13
VA	NORFOLK	37.07	7.49
VA	RICHMOND	36.75	7.63
VA	ROANOKE	37.80	8.13
WA	OLYMPIA	4.65	1.24
WA	SEATTLE (APT)	7.27	1.60
WA	SEATTLE (CITY)	5.06	1.46
WA	SPOKANE	10.50	1.74
WA	STAMPEDE PASS	7.29	1.29
WA	WALLA WALLA	11.26	1.51
WA	YAKIMA	6.90	1.25
WV	BECKLEY	45.71	10.97
WV	CHARLESTON	43.37	9.42
WV	ELKINS	44.93	10.33
WV	HUNTINGTON	44.38	9.57
WV	PARKERSBURG	44.00	9.91
WI	GREEN BAY	34.79	6.49
WI	LA CROSSE	40.15	9.29
WI	MADISON	40.62	7.96
WI	MILWAUKEE	35.31	6.40
WY	CASPER	34.26	7.35
WY	CHEYENNE	49.85	15.41
WY	LANDER	31.71	7.05
WY	SHERIDAN	35.59	9.03

TECHNICAL REPORT STANDARD TITLE PAGE

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Final Report

16. ABSTRACT

Computer simulations and laboratory tests were used to evaluate the hazard posed by lightning flashes to ground on the SPS rectenna and to make recommendations on a lightning protection system for the rectenna. The distribution of lightning over the lower 48 of the continental United States was determined, as were the interactions of lightning with the rectenna and the modes in which those interactions could damage the rectenna. The studies showed that lightning protection was both required and feasible. Several systems of lightning protection were considered and evaluated. These included two systems that employed lightning rods of different lengths and placed on top of the rectenna's billboards and a third, distributed system. The distributed system is similar to one used by power distribution companies; it consists of short lightning rods all along the length of each billboard that are connected by a horizontal wire above the billboard. The system that not only affords greater protection than the others considered but offers easiest integration into the rectenna's structural design, was the distributed lightning protection system.

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